

Integration of TV White Space and Femtocell Networks

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To All People I Love

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Abstract

Femtocell is an effective approach to increase system capacity in cellular networks. Since traditional Femtocells use the same frequency band as the cellular network, cross-tier and co-tier interference exist in such Femtocell networks and have a major impact on deteriorating the system throughput. In order to tackle these challenges, interference mitigation has drawn attentions from both academia and industry. TV White Space (TVWS) is a newly opened portion of spectrum, which comes from the spare spectrum created by the transition from analogue TV to digital TV. It can be utilized by using cognitive radio technology according to the policies from telecommunications regulators. This thesis considers using locally available TVWS to reduce the interference in Femtocell networks. The objective of this research is to mitigate the downlink cross-tier and co-tier interference in different Femtocell deployment scenarios, and increase the throughput of the overall system.

A Geo-location database model to obtain locally available TVWS information in UK is developed in this research. The database is designed using power control method to calculate available TVWS channels and maximum allowable transmit power based on digital TV transmitter information in UK and regulations on unlicensed use of TVWS. The proposed database model is firstly combined with a grid-based resource allocation scheme and investigated in a simplified Femtocell network to demonstrate the gains of using TVWS in Femtocell networks.

Furthermore, two Femtocell deployment scenarios are studied in this research. In the suburban Femtocell deployment scenario, a novel system architecture that consists of the Geo-location database and a resource allocation scheme using TVWS is proposed to mitigate cross-tier interference between Macrocell and Femtocells. In the dense Femtocell deployment scenario, a power efficient resource allocation scheme is proposed to maximize the throughput of Femtocells while limiting the co-tier interference among Femtocells. The optimization problem in the power efficient scheme is solved by using sequential quadratic programming method. The simulation results show that the proposed schemes can effectively mitigate the interference in Femtocell networks in practical deployment scenarios.

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List of Abbreviations

2G	Second Generation
3G	Third Generation
3GPP	The 3rd Generation Partnership Project
AP	Access Point
AWGN	Additive White Gaussian Noise
BS	Base Station
BW	Bandwidth
CCI	Co-channel Interference
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CMS	Cognitive Mobile Stations
CogNeA	Cognitive Networking Alliance
CPE	Consumer Premises Equipment
CR	Cognitive Radio
CWN	Cognitive Wireless Networks
DA	Distributed Antenna
DL	Downlink
DSL	Digital Subscriber Line
ECMA	European Computer Manufacturers Association
EIRP	Effective Isotropic Radiated Power
eNB	E-UTRAN NodeB
EU	European Union
FCC	Federal Communications Commission

FDD	Frequency Division Duplex
Femto BS	Femtocell Base Station
Femto UE	Femtocell User Equipment
FP 7	Framework Programmes 7
GSM	Global System for Mobile Communication
Home eNB	Home E-UTRAN Node B
ICI	Inter-cell Interference
IEEE	The Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
ITU	International Telecommunications Union
LOS	Line-Of-Sight
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
Macro BS	Macrocell Base Station
Macro UE	Macrocell User Equipment
NGMN	Next Generation Mobile Networks
NGR	National Grid Reference
NLOS	Non-Line-Of-Sight
Ofcom	The Federal Office of Communication in UK
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiplexing Access
QoS	Quality of Service
PL	Path Loss
RAN	Radio Access Network
RF	Radio Frequency
RRM	Radio Resource Management

RSPG	Radio Spectrum Policy Group
SDR	Software Defined Radio
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
SQP	Sequential Quadratic Programming
TDD	Time Division Duplex
TTI	Transmission Time Interval
TVWS	TV White Space
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunication System
UTRA	Universal Terrestrial Radio Access
UWB	Ultra Wide Band
WCDMA	Wideband Code Division Multiple Access
WiFi	Wireless Fidelity
WiMax	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Network
WRAN	Wireless Regional Access Network
WSD	White Space Device

Chapter 1 Introduction

1.1 Introduction

Nowadays, the increasing demand for higher data rate in wireless communications is becoming more and more apparent, which has triggered the development of new communication standards with higher capacity and better coverage, such as Worldwide Interoperability for Microwave Access (WiMax) by IEEE 802.16e, and Long Term Evolution (LTE) by the Third Generation Partnership Project (3GPP). The promising way to increasing wireless system capacity is getting transmitter and receiver closer to each other [1], which can lead to higher quality transmission links and more spatial reuse. A popular and effective approach from both academia and industry is small cell deployment. The small cell is low-powered radio access node that operates in licensed and unlicensed spectrum. It typically has a range of ten meters to several hundred meters [2].

Generally speaking, small cells include Femtocells, Picocells, Metrocells and Microcells, broadly increasing in size from Femtocells to Microcells. To deploy small cells effectively, reliable high speed backhaul links with minimal infrastructure investment are essential. Some types of small cells are not widely deployed so far because providing appropriate backhaul connections to small cell base stations are expensive and complicated. Femtocells are the most widely deployed type of small cells, since they can use the home broadband connection as the backhaul, e.g. Digital Subscriber Line (DSL). Femtocells are also called home base stations (BSs), which are short-range-low-cost-low-power BSs installed by consumers for better indoor signal reception. In comparison with other techniques for increasing system capacity, such as distributed antenna [3] and Microcells [4], the advantage of Femtocells is that the upfront and maintenance cost is little. The Femtocell market has experienced rapid growth to date. By February 2013, there have been 46 commercial services and a total of 60 deployment commitments, including AT&T, Sprint, Orange, Telefonica, T-Mobile and Vodafone, etc. Among them, Sprint's deployment reached 1 million units by October 2012 and AT&T's deployment has also reached similar numbers [5].

One of the major technical challenges of Femtocell networks is interference management. Since traditional Femtocells use the same frequency band as the cellular network, there exist the cross-tier interference between Femtocell and Macrocell, and the co-tier interference between Femtocells [6]. The interference problem affects the Femtocell networks performance significantly. It is essential to develop effective interference management schemes that would mitigate the interference in order to enhance the throughput of Femtocell networks. Current solutions include fractional frequency reuse, transmit power control and collaborative resource negotiation etc. [7]. These solutions are generally based on the licensed cellular frequency band, and have limited interference improvement at the expense of system complexity.

The newly opened portion of spectrum TV White Space (TVWS) provides a new option for Femtocell networks. TVWS comes from the spare spectrum created by the transition from analogue TV to digital TV. Regulators such as Federal Communications Commission (FCC) and Office of Communications (Ofcom) have permitted unlicensed use in TVWS, on the condition that not interfering with incumbent TV users. The feasibility of using TVWS spectrum for future home networking services has been discussed in [8], which states that with the use of cognitive radio (CR) technology, the TVWS offers a potential option to provide high data-rate services in wireless home networks. Among several CR mechanisms, Geo-location database method is regarded as the most promising mechanism for TVWS spectrum detection as suggested by Ofcom [9], and has drawn attentions and efforts from both academia and industry.

The research in this thesis considers designing a Geo-location database model to obtain locally available TVWS information, and designing appropriate resource allocation schemes based on the available TVWS to reduce the interference in Femtocell networks in different deployment scenarios.

1.2 Research Scope

This thesis presents the research on the integration of TVWS and Femtocell networks. OFDMA-based Femtocell networks in different deployment scenarios are considered in this thesis. Specific research aspects included are:

- How to obtain locally available TVWS spectrum resource information including available TVWS channels and associated maximum transmit power based on location information.
- How to design the resource allocation scheme that can utilize the locally available TVWS in a Femtocell network.
- How to design appropriate resource allocation scheme based on the available TVWS for mitigating the cross-tier interference in suburban Femtocell deployment scenario.
- How to design appropriate resource allocation scheme based on the available TVWS for mitigating the co-tier interference in dense Femtocell deployment scenario.

The objective of this research is to design a system architecture that consists of the cognitive mechanism to obtain locally available TVWS information, and the resource allocation schemes to utilize the available TVWS to reduce the interference in Femtocell networks. Regulatory requirements and feasibility are considered in designing the cognitive mechanism. Moreover, different Femtocell deployment models are considered in the resource allocation schemes to meet the interference mitigation challenges in suburban deployment and dense deployment scenarios, respectively.

1.3 Research Contributions

The main contributions of the research work in this thesis are introduced as follows:

1) Geo-location database model for cognitive access to TVWS

This thesis proposes a Geo-location database model using power control method to obtain locally available TVWS information, including available TVWS channels and associated maximum transmit power based on location information. It is designed according to digital TV (DTV) transmitter information in UK and regulations on unlicensed use of TVWS. The proposed database model can provide TVWS information to CR stations for resource allocation, and protect primary TV users from harmful interference due to the secondary use of TVWS. The results of the proposed database model are compared and verified by a keep-away region Geo-location database model and an existing DTV transmitter database in UK. Then, based on the available TVWS, a grid-based plus interference avoidance resource allocation scheme is proposed for a simplified Femtocell network to investigate the system performance of using TVWS in Femtocell networks.

2) Resource allocation scheme using TVWS for cross-tier interference mitigation in suburban Femtocell deployment

Based on the Geo-location database model, a resource allocation scheme using locally available TVWS is proposed to mitigate the downlink cross-tier interference in suburban Femtocell deployment, where Macro UEs are interfered by nearby Femtocells. The proposed scheme assesses which of the Femtocells are causing cross-tier interference to one or more Macro UEs at a given point, and then those Femtocells are temporarily allocated with the available TVWS spectrum resource to avoid their potential interference on nearby Macro UEs. Moreover, the proposed scheme is investigated in the cell edge scenario, where the SINR of Macro UEs may get even lower due to the cross-tier interference from nearby Femtocells.

3) Power efficient resource allocation scheme for co-tier interference mitigation in dense Femtocell deployment

For the dense Femtocell deployment in urban area, the cross-tier interference between Femtocells and Macro UEs can be mitigated by using TVWS spectrum for Femtocells, with the aid of Geo-location database. However, the co-channel interference between Femtocells becomes dominant due to the high density of Femtocells reusing the TVWS spectrum. In this case, a power efficient resource allocation scheme is proposed to maximize the throughput of Femtocells while limiting the co-tier interference among Femtocells. A sequential quadratic programming (SQP) method is applied in solving the power allocation optimization problem in the proposed scheme.

1.4 Author's Publications

1. F. Peng, N. Wang, Y. Gao, L. Cuthbert, X. Zhang, "Geo-location Database based TV White Space for Interference Mitigation in LTE Femtocell Networks," The Second IEEE International Workshop on Emerging Cognitive Radio Applications and Algorithms, IEEE WoWMoM 2013, Madrid, Spain, 4-7 June 2013.
2. F. Peng, Y. Gao, L. Cuthbert, "Reviews on Cognitive Access to TV White Space," Chinacom 2012, C3Hetnet workshop, Kunming, China, 8-10 August 2012.
3. X. Zhang, Y. Gao, Z. Yan, X. Jiang, F. Peng, Laurie G. Cuthbert and Wenbo Wang, "Cognitive and Cooperative Communications in Wireless Heterogeneous Networks (HetNet): Current Status and Technical Perspectives," 2012 IEEE International Conference on Wireless Information Technology and Systems, Maui, Hawaii, 11-16 November 2012.

4. F. Peng, Y. Gao, Y. Chen, K. K. Chai, L.G. Cuthbert, "Using TV White Space for Interference Mitigation in LTE Femtocell Networks," 2011 IET International Conference on Communication Technology and Application (ICCTA), Beijing, China, 14-16 October 2011.
5. F. Peng, Y. Gao, Y. Chen and L. Cuthbert, "Using TV White Space for Femtocell Aided Future Mobile Network," Annual International Conference on Green Information Technology (GREENIT), Singapore, 25-26 October 2010.

1.5 Thesis Organization

The rest of this thesis is organized as follows:

Chapter 2 introduces the background including the overview of Femtocell networks, interference management in Femtocell networks, the overview of TVWS, cognitive access methods to TVWS, and the SQP method used in this thesis.

Chapter 3 presents the simulation scenarios and simulators. Two simulators are introduced in this chapter. The simulator for a simplified Femtocell network is firstly introduced. Then, the simulator for a two-tier OFDMA Femtocell network is presented, in which two Femtocell deployment models are implemented for suburban deployment and dense deployment scenarios respectively. The key modules and channel models in these two simulators are also introduced.

Chapter 4 discusses the proposed power-control Geo-location database model for obtaining available TVWS information. A grid-based plus interference avoidance resource allocation scheme using TVWS is also proposed and investigated in a simplified Femtocell network.

Chapter 5 investigates the cross-tier interference mitigation in suburban Femtocell deployment. A novel system architecture consists of the Geo-location database and a

resource allocation using TVWS is proposed to solve the downlink cross-tier interference problem.

Chapter 6 researches the co-tier interference mitigation in dense Femtocell deployment. The problem of resource allocation is formulated, and a power efficient resource allocation scheme is proposed to maximize the throughput of Femtocells while limiting the co-tier interference among Femtocells. The process of using SQP method to solve the power allocation optimization problem in the proposed scheme is also presented.

Chapter 7 concludes the work of this thesis, and the direction of future work is discussed.

Chapter 2 Background

2.1 Introduction

In this chapter, the background knowledge used in this thesis is introduced, including Femtocell networks, TVWS and constrained nonlinear optimization method, e.g. SQP method. These lay out foundations for the research work carried out in the following chapters.

2.2 Overview of Femtocell Networks

2.2.1 The Concept of Femtocells

In modern wireless communication network, there is an increasing demand on higher network capacity. A number of technologies and standards have been researched and developed to meet this increasing demand, such as the 3GPP's LTE and LTE-Advanced, 3GPP2's Ultra Mobile Broadband (UMB), and WiMAX. Research studies on wireless usage also show that more than 50% of all voice calls and more than 70% data traffic originated from indoor environment [1]. However, conventional mobile cellular network has poor indoor coverage due to the high attenuation losses, which makes it difficult to achieve high quality signal and hence high data rates for indoor devices. Solutions to enhance network capacity and indoor coverage include Microcells which are operator installed cell towers [4], and Distributed Antennas which are operator installed spatially separated antenna elements [3], etc. The disadvantages of these solutions are high costs related to the installation and maintenance of new infrastructures; moreover, they do not guarantee reliable indoor coverage [1].

Femtocell as a cost-effective approach to improving network capacity and indoor coverage has drawn a lot of attention. It is a home base station with short range, low cost and low power, installed by consumers to provide wireless voice and broadband

services [6]. Femtocell Base Station (Femto BS) is linked with cellular networks via a broadband connection, such as DSL or cable, thus can offload the traffic in cellular networks by re-directing indoor traffic into the IP backbone to save the limited wireless resource. In this way, Macro BS can use the saved wireless resource to provide better reception to other mobile users to improve the Macrocell reliability. A typical Femtocell deployment scenario is shown in Figure 2.1.

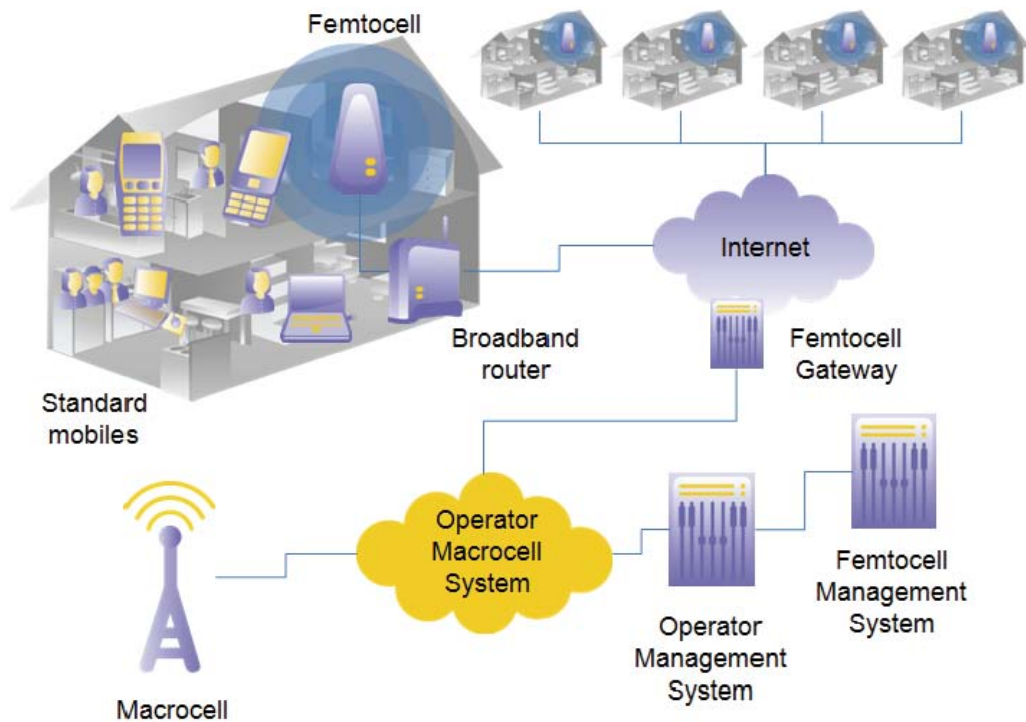


Figure 2.1 A typical Femtocell deployment scenario [2]

2.2.2 Types of Femtocells

In recent years, different types of Femtocells have been developed according to various air interface technologies and standards.

1) 2G Femtocells

The 2G Femtocells are based on the Global System for Mobile Communication (GSM) air interfaces. The advantage of 2G Femtocells is the low cost, while the disadvantage is mainly that it cannot provide high data rate services due to the limitations of General Packet Radio Service (GPRS) [10]. Therefore, research suggests that the development of 2G Femtocell is more feasible in developing countries where GSM cellular network is widely used, and voice calls are the mostly used services [11].

2) 3G Femtocells

The 3G Femtocells mainly use Wide Code Division Multiple Access (WCDMA) air interface of Universal Mobile Telecommunication system (UMTS), which is also known as UMTS Terrestrial Radio Access (UTRA). The 3G Femtocells can provide higher data rates because of the UMTS technology has the capability of connecting through IP based networks [12]. In the 3GPP standards, 3G Femtocells are referred as Home Node Bs (HNBs).

3) OFDMA Femtocells

The basic idea of an OFDM system is to use narrow, mutually orthogonal subcarriers to carry data. OFDM divides the high rate data stream into several parallel, low rate data streams. Each low rate data stream is assigned to one subcarrier for transmission. An illustration of OFDM subcarriers is shown in Figure 2.2. At the sampling instant of a single subcarrier, the other subcarriers have a zero value. Therefore, the subcarriers are orthogonal to each other. OFDMA is a multiple access version of the OFDM scheme, and is achieved by assigning different groups of subcarriers to different users.

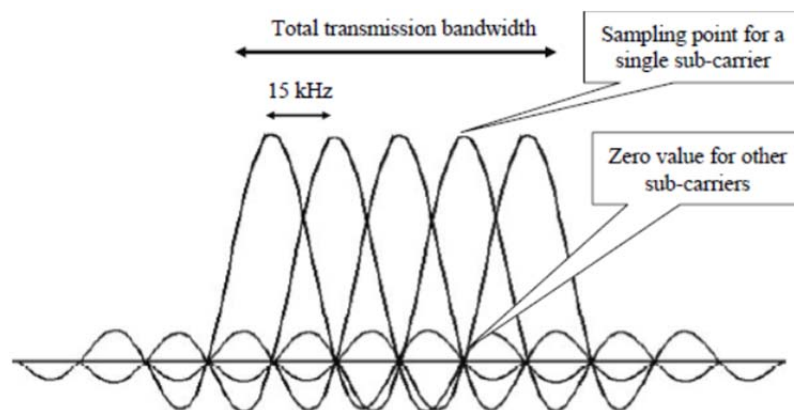


Figure 2.2 OFDM subcarriers [13]

OFDMA Femtocells are based on the OFDMA technology. These Femtocells are advanced in exploiting channel variations in both frequency and time domains for interference avoidance, and providing various high data rates to different users [14]. LTE Femtocells are under this category, and are also referred to as Home evolved Node Bs (HeNBs). An example structure of OFDMA Femtocell (e.g. LTE Femtocell) is shown in Figure 2.3.

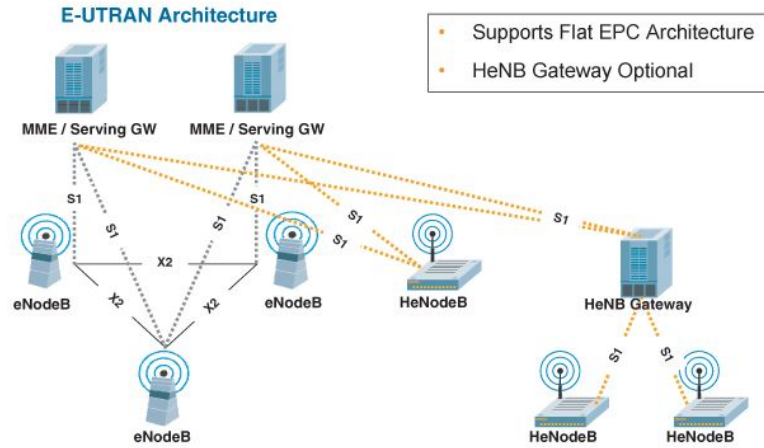


Figure 2.3 LTE Femtocell (i.e. HeNB) network structure [15]

4) Cognitive Femtocells

Cognitive Femtocells are cognitive radio enabled Femtocells with the cognitive functionalities of opportunistic spectrum access [16]. Traditional Femtocells share the same licensed spectrum bands as Macrocells. The capacity of Femtocell networks is limited because of the scarcity of spectrum and the interference with Macrocells and other Femtocells. In the case of spectrum shortage, or for interference management purpose, cognitive Femtocells can utilize spectrum opportunities (e.g. TVWS or spectrum holes) in the local environment [17]. This can be achieved via database approach or spectrum sensing approach.

The database approach is to access the available spectrum list from a central database. This approach can be applied to slowly-changing spectrum, such as TV bands which have a relatively static characteristic. In the United States, the FCC accepts the management of TVWS by a White Space database (WSDB) approach [18]. The WSDB keeps the up-to-date spectrum availability information by applying secure and trusted registration of devices. For spectrum sensing approach, it can be achieved locally in Femto BSs, or cooperatively by exchanging sensing data between neighbour Femtocells [14].

2.2.3 Technical Challenges of Femtocells

Femtocells bring a lot of advantages in terms of capacity improvement and better indoor coverage, however, there are still several technical challenges need to be addressed.

1) Access Methods

There are three access methods according to which Femtocells can be configured to decide what user can access a specific Femtocell.

- Open Access Method

In this method, all users including nearby Macro UEs and local users are allowed to connect to the Femtocell. The open access method is beneficial to the overall capacity of the network, since Macro UEs with poor signal reception from the Macro BS can be served by the nearby Femtocells [19]. Interference from Femto BS to nearby Macro UEs can also be avoided in this method, since potential victim Macro UEs can connect to the Femtocell as well.

However, open access incurs more handoffs and signalling. Subscribers who paid fees for Femtocell connections are also not willing to make their Femtocells free to use for other users.

- Closed Access Method

In this method, only subscribed users are allowed to access the Femtocell. This method is likely to be used in home environment. For example, the use of Femtocells is restricted to residents at home with Femtocell deployed. In this method, nearby Macro UEs which are also located in the Femtocell coverage will experience low signal quality due to the strong interference from Femtocells [20].

- Hybrid Access Method

In this method, non-subscribed users are allowed to access the Femtocells. But the available spectrum resource will be restricted, so that the service performance of subscribed users is guaranteed [21].

2) Time Synchronization

The network time synchronization is necessary in Femtocells to minimize multi-access interference and avoid overlapping of uplink and downlink transmission periods. However, it is not trivial to install high precision crystal oscillators in Femtocells due to the low-cost requirement for the target consumer market. To achieve reliable time synchronization, there are some other approaches.

GPS receiver is one of the approaches. It can provide accurate time synchronization in a cost-effective way. However, the performance of GPS approach depends on the GPS signal reception quality in the Femtocell location. If the signal is poor due to walls penetration loss, the synchronization will also be inaccurate. IEEE-1588 Precision Timing Protocol is another feasible approach [22], but in order to make it perform efficiently over asymmetric backhaul links, e.g. ADSL, some further modifications are necessary.

3) Mobility Management

Due to the small coverage size of Femtocells, many handoffs will be triggered when users enter or leave the coverage area, incurring a certain number of network signalling. This would be more severe in the case of Femtocells with open access where more users can get access to the Femtocell [23]. Different handoff mechanisms for different Femtocell deployment scenarios are needed to be designed to reduce the potential handoffs and the corresponding signalling cost.

4) Security

Security issue is also an important challenge in Femtocell. Since Femto UE data is transmitted to core networks via IP-based broadband backhaul instead of dedicated communication channels, and the data is vulnerable to malicious attacks from the internet, e.g. eavesdropping, hacking etc. To cope with this problem, necessary security mechanisms (e.g. Firewalls) should be implemented in operator's Femtocell gateways through which Femto BSs connect to the internet [24].

2.2.4 Interference Management in Femtocell Networks

Besides of the challenges discussed in section 2.2.3, one of the major technical challenges of Femtocell networks is interference management, which is also the main focus of this research. Thus it is discussed separately in this section.

1) Types of Interference in Femtocell Networks

In a two tier Femtocell network architecture that consists of a central Macrocell and underlay/overlay Femtocells. There are mainly two types of interference:

A. Cross-tier Interference

This type of interference occurs among different tiers of the network, e.g. interference between Femtocells and Macrocells. Traditional Femtocell deployment shares the same frequency spectrum with Macrocells. In the downlink case, when a Macro UE is near to a Femtocell, it receives strong downlink cross-tier interference from the nearby Femto BS; while when a Femtocell is located near to a Macro BS, users in that Femtocell receives strong downlink cross-tier interference from the Macro BS as well. In the uplink case, Femto UEs and Macro UEs act as aggressors, and produce uplink cross-tier interference to nearby Macro BSs and Femto BSs, respectively.

B. Co-tier Interference

This type of interference occurs among the same tier of the network, e.g. interference between neighbouring Femtocells. For example, a Femto UE can act as an aggressor and cause uplink co-tier interference to its neighbouring Femto BSs that are operating in the same spectrum. On the other hand, a Femto BS can also act as an aggressor and cause downlink co-tier interference to UEs in its neighbouring Femtocells.

2) Interference Scenarios

Figure 2.4 illustrates all possible interference scenarios in an OFDMA Femtocell network. As summarized in Table 2.1, there are total 6 interference scenarios among Macro BS, Macro UE, Femto BS and Femto UE. The research of this thesis will focus on the downlink cross-tier and co-tier interference scenarios.

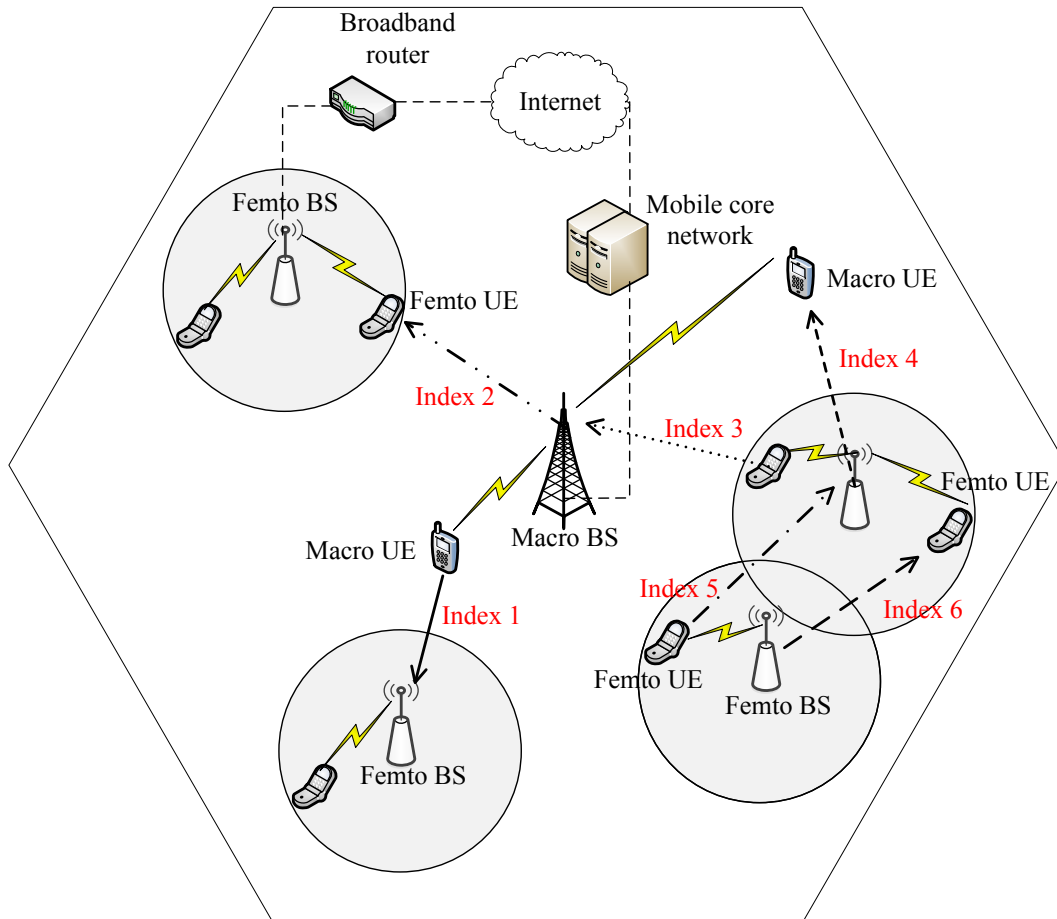


Figure 2.4 Interference scenarios in OFDMA Femtocell networks [7]

Table 2.1 Summary of interference scenarios in OFDMA Femtocell networks

Index	Aggressor	Victim	Interference Type	Transmission Mode	Symbol
1	Macro UE	Femto BS	Cross-tier	Uplink	————→
2	Macro BS	Femto UE	Cross-tier	Downlink	— . . —→
3	Femto UE	Macro BS	Cross-tier	Uplink→
4	Femto BS	Macro UE	Cross-tier	Downlink	- - - -→
5	Femto UE	Femto BS	Co-tier	Uplink	- . - ->
6	Femto BS	Femto UE	Co-tier	Downlink	- - - -→

As the index 4 in Figure 2.4 indicates, when a Macro UE is near to or even within a Femtocell's coverage, the Macro UE experiences severe downlink cross-tier interference from the Femto BS [25]. In the case of closed access Femtocells, this interference problem becomes even more severe. For example, a Macro UE that is in very close proximity to a house cannot access to the Femtocells in that house, and the power leakage through windows and doors from a Femto BS in the house is a significant source of cross-tier interference to that Macro UE.

Macro UEs located in the cell edge area of Macrocell experiences poor signal reception from Macro BS due to the high path loss and shadowing effect, and thus low Signal to Interference plus Noise Ratio (SINR). In this case, the cross-tier interference from nearby Femto BSs makes the SINR of Macro UEs even worse.

The downlink co-tier interference between Femtocells is indicated by index 6 in Figure 2.4. This type of interference normally happens in dense Femtocell deployment. For example, Femtocells can be deployed very close to each other in apartments of a building in city urban area, and wall separations are not enough to reduce the interference level. In this case, a Femto UE may receive strong co-tier interference from many neighbouring Femto BSs. However, the co-tier interference will be less significant in suburban areas, where houses with Femtocell installed are located sparsely.

Normally, Femtocells are located in a certain distance to a Macro BS. Because of small coverage area, transmission path between Femto BS and Femto UE is very short. Therefore Femto UE receives very strong signals from Femto BS. In this case, the downlink cross-tier interference from Macro BS to Femto UEs indicated by index 2 in Figure 2.4 is not significant.

Based on the study, this thesis will focus on the study of following two interference scenarios: 1) Femto BS to Macro UE downlink cross-tier interference scenario; and 2) Femto BS to Femto UE downlink co-tier interference scenario.

3) Approaches on Interference Management of Femtocell Networks

The research on interference management of Femtocell networks is very active, and many schemes have been proposed. Different approaches on solving downlink interference scenarios in Femtocell networks are introduced as follows:

A. Fractional Frequency Reuse and Resource Partitioning

The main idea of this method is to divide the entire frequency spectrum into several sub-bands, and each sub-band is differently assigned to sub-area of Macrocell and Femtocells [26]. In this way, the frequency band for Macrocell and Femtocell is not overlapped, so that interference between Macrocell and Femtocell can be mitigated. In [27], an interference management scheme for LTE Femtocells is proposed. This scheme mitigates the downlink cross-tier interference by assigning sub-bands that are not being used in the Macrocell sub-area to Femtocells.

In [28], the authors perform resource partition based on Resource Blocks (RB), the idea is to deny Femtocell access to RBs that used by nearby Macro UEs. By doing this, the interference suffered by Macro UEs can be reduced, but Femtocell throughput is also reduced. A graph colouring scheme for co-tier interference mitigation is proposed in [29], in which the interference graph of Femtocells is firstly generated based on the measured SINR of Femtocells, and then sub-channels are allocated to Femtocells accordingly to ensure that sub-channels are not used by neighbouring Femtocells.

B. Power Control

This approach focuses on reducing transmit power of Femto BSs, so that the cross-tier interference between Femtocell and Macrocell can be mitigated. The advantage is that Macrocell and Femtocell can use the entire bandwidth with interference coordination [30]. In [31], the authors propose a decentralized carrier-sensing approach to regulate Femtocell transmit powers based on their locations. In [32], a distributed power control scheme is proposed for downlink transmission of OFDMA-based Femtocells by formulating the power control problem as a non-cooperative game. Macro UEs are referred as the leader players and the Femto UEs are referred as the follower players. The players are competing with each other in a

non-cooperative manner to reach Nash equilibrium, which is the solution of the power control problem.

C. Clustering of Femtocells

In [33], a framework is proposed to reduce downlink interference for OFDMA-based closed access Femtocell networks. In this proposed scheme, part of the entire spectrum is dedicated to Macro UEs, and the rest is shared by Macro UEs and Femto UEs. Femtocells are allocated into different frequency reuse clusters to avoid co-tier and cross-tier interference. The clustering is based on threshold distances which are calculated according to their locations. Femto UEs of different Femtocell in the same cluster will use the same sub-channels.

In [34], an energy-efficient scheme is proposed. In this scheme, closed access Femtocells are grouped in a neighbourhood area according to their locations. Co-tier interference among neighbouring Femtocells is mitigated by reducing the unnecessary sending of preambles in Femtocells that no active users in its coverage zone.

D. Cognitive Approach

In the cognitive approach, Femtocells utilize spectrum sensing to obtain the knowledge of neighbours in order to perform the interference mitigation [35]. In [36], an interference management scheme is proposed for downlink co-tier interference scenario in an OFDMA-based Femtocell network. In the proposed scheme, the spectrum usage information of neighbouring Femtocells can be sensed by Femto BSs. Femto BSs exchange path-loss information and usage of spectrum via Femtocell gateway, e.g. an intermediate node between Femto BS and mobile core network. Each Femto BS can estimate potential co-channel interference based on the neighbours' information and then select appropriate sub-channels to avoid interference.

In [37], a cross-tier interference avoidance scheme for OFDMA Femtocells is proposed. In this scheme, the Femto BSs receive Macro UEs scheduling information from Macro BSs, and compare them with their own sensing results to find appropriate spectrum to use, so that the cross-tier interference is avoided.

2.2.5 Standardization Progress and Deployment

The standardization progress of Femtocells is under fast development. There is a non-profit organization called Femto Forum founded in 2009, aiming at standardization, regulation and interoperability, marketing and promotion for Femtocell technology [38]. This organization consists of members ranging from telecommunication operators and Femtocell vendors, has carried out a lot work in facilitating Femtocell development.

The 3GPP in cooperation with Femto Forum and Broadband Forum released the world's first Femtocell standard worldwide in April 2009 [39]. This standard paves the way for Femtocell standardization and forms part of 3GPP's Release 8 and enables the interoperability between Femto BSs from different vendors.

Furthermore, the concept of Femtocell also has been applied to existing wireless standards, for example, LTE has included Femtocell into its standard, in which it is called Home eNode B [40]. It is also included in the recent 3GPP Technical Report on LTE-A Release 12 in October 2012 [41].

The Femtocell market has experienced rapid growth to date. By February 2013, there have been 46 commercial services and a total of 60 deployment commitments. In UK, Vodafone has conducted their trials of 3G Femtocells in early 2008 and has provided the Femtocell service, named "Vodafone Sure Signal" to its customers [42]. In US, the network operator Sprint provides "Airwave" Femtocell in CDMA 1x EVDO network. While another operator Verizon has started exploiting Femtocell in "Verizon Home Network Expander" program in CDMA networks [43]. According to market status report [5], Sprint's Femtocell deployment reached 1 million units by October 2012 and AT&T's deployment has also reached similar numbers.

2.3 Overview of TV White Space

2.3.1 The Concept of TV White Space

In telecommunications, the term White Space refers to frequencies that have been allocated to a broadcasting service but not used locally [44]. Broadcast television operates in the VHF/UHF spectrum band. In order to ensure TV broadcast quality, most countries regulatory organizations prohibit the use of unlicensed devices in TV bands, except for remote control, medical telemetry machines and wireless microphones.

As the development of digital broadcasting technologies, most developed countries are in the process of converting TV stations from analogue to digital, which is also called digital switchover. The process has been completed in 2009 in US and 2012 in UK. The similar switchover process is also taking place or planned to launch in EU and other countries around the world [45].

During this switchover, a certain amount of spectrum that occupied by analogue channels has been freed up due to the higher spectrum efficiency of digital TV (DTV). Among these cleared spectrums, spectrum in 800MHz band (790-862MHz) has been auctioned off by Ofcom to UK mobile operators for 4G mobile broadband services in March 2013 [46]. Ofcom also has proposed that the cleared spectrum in the 600MHz band (550-606MHz) could be made available for use by a number of candidate services in the short term in the UHF strategy statement released in November 2012. However, when the 700MHz band which is currently carrying DTV service is released for mobile broadband, the 600MHz band will then be used for re-planned DTV service [47]. Moreover, for avoiding co-channel or adjacent channel interference between TV stations, only a subset of the TV channels reserved for DTV broadcasting are actually used in a given geographic area. These spectrums (known as interleaved spectrum) can become available for secondary uses on a geographical basis, and are referred as TV White Space (TVWS) [48].

The great attractiveness of TVWS comes from its advantage in the combination of bandwidth and coverage. Compared with WiFi and 3G signals, TV signals can

penetrate buildings more easily [45]. Hence, these bands can be used for a wide range of potential new services, including last mile broadband access in urban area, wireless broadband in rural areas [49], licensed-exempt mobile broadband and wireless network for digital homes. Furthermore, the signal wavelength in the TV band is sufficiently short, so that small antennas can be used, which makes it suitable for portable devices [50].

2.3.2 Regulatory Development of TV White Space

Due to the great attractiveness of TVWS and the intensive demand to reduce the burden of current spectrum, there has been a lot of regulatory effort taking place on TVWS. Regulatory organizations in US and UK are leading the regulatory development.

In US, the regulatory organization Federal Communications Commission (FCC) has allowed to opportunistic use of TV bands in 2004 [51], and cognitive radio device (cognitive device) prototypes have been submitted to FCC by many companies, such as Motorola, Philips, Microsoft in 2008 [48]. FCC carried out a series of strict tests on the prototypes, and proposed a second report and order to regulate the unlicensed operation of cognitive devices in TVWS [52]. Specially, in order to minimize the impact of harmful interference due to the hidden node problem, FCC required that cognitive devices should be able to sense signals down to -114dBm. In the FCC report, it also concludes that licensed exemption is the best way to facilitate innovative application, while licensing is difficult to define and would need to keep being awarded to users when there are changes on available TVWS, for example, the TV transmitter coverage is re-planned.

In the UK, the regulatory organization Ofcom also proposed to allow license exempt use of interleaved spectrum (i.e. White Space) for cognitive devices in its Digital Dividend Review Statement, which is released in December 2007 [53]. In this statement, Ofcom also pointed that there can be seen great scope for cognitive equipment using interleaved spectrum, not only from the technology point of view but also from the economics point of view. According to documents published by

FCC, Ofcom also proposed a number of technical parameters for the cognitive use of interleaved spectrum on licensed exempt basis.

In European Union, Radio Spectrum Policy Group (RSPG) is a high-level advisory group that assists the European Commission in the development of radio spectrum policy. In the report of RSPG opinion on cognitive technologies that was released in February 2011, it is highlighted that the use of TVWS in the UHF band can be one of the first applications of cognitive radio [54]. The European Conference of Postal and Telecommunications Administrations (CEPT) is one of the key organisations for harmonising telecommunications regulation in Europe. The Electronic Communications Committee (ECC), within the CEPT, has formed a working group for Spectrum Engineering (i.e. the so called "SE 43"). The SE 43 group focuses on CR systems and white spaces. The work in SE 43 has led to the release of the ECC report 159 in January 2011 [55]. This report discusses the technical and operational requirements for the operation of CR systems in the TVWS (470-790MHz), and the report also defines a set of criteria for the operation of white space devices to protect primary services. Two reports that are complementary to ECC report 159 have also been approved in January 2013. They are ECC report 185 that directly complements report 159 for further definition of technical and operational requirements for the operation of white space devices [56], and report 186 that covers topics of geo-location approach [57].

The potential advantages of TVWS depend on the availability of TVWS. Figure 2.5 shows allocations of the UHF spectrum in UK after digital switchover [58]. Channels marked in green with total 128 MHz bandwidth are the cleared spectrum during the transition. Ofcom will license it by auctions. Channels marked in purple with total 256 MHz is the interleaved spectrum which can be used for licensed-exempt use by cognitive devices on a geographical basis. The pink one is reserved for wireless microphone use.



Figure 2.5 Allocations of the UHF spectrum in UK after DSO [58]

The availability of TVWS varies in different locations. For example, Figure 2.6 shows the TVWS availability in Bristol, Liverpool, London and Southampton (from left to right and top to bottom), respectively. Blue bars indicate the vacant TV channels. Studies show that in UK there are over 50% of locations that have more than 150MHz of interleaved spectrum, and about 100MHz at 90% of locations is available for cognitive access [9].

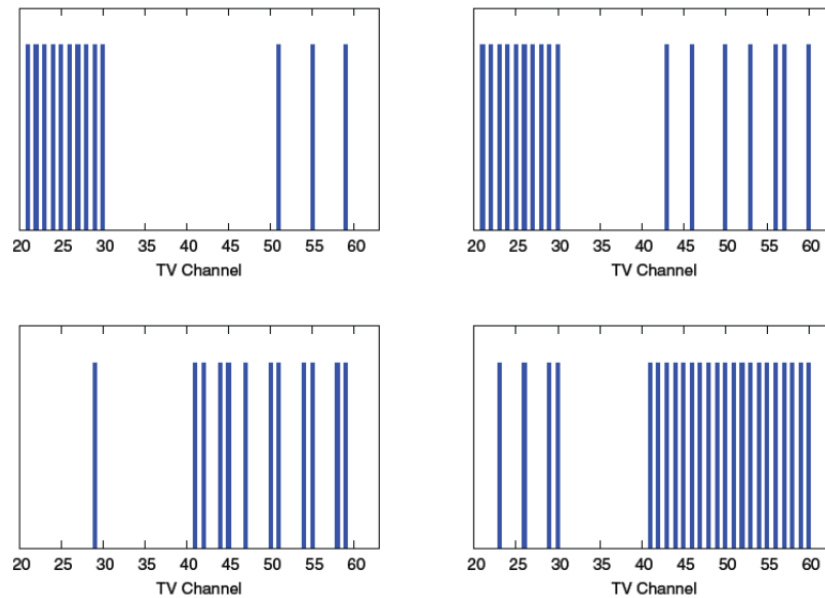


Figure 2.6 TVWS availability in 4 UK cities [45]

There are two important aspects to discuss on utilizing TVWS. One is that high power cognitive device operating on a vacant TV channel may cause interference to adjacent occupied channels. If adding constraints on using channels whose adjacent channels are used for primary purpose, the available channels will be reduced

greatly in most locations. The other one is that for a given area not all available channels are contiguous as shown in Figure 2.6. However, in most wireless technologies, the modulation scheme requires a contiguous portion of spectrum. This will also influence the access to TVWS for some wireless technologies.

There is a section about “Enable white space spectrum opportunities” in the Ofcom 2012-13 annual plan [59], which states that Ofcom will continue to work on enabling white space access on a licence-exempt basis in the UHF TV band. Moreover, Ofcom has also published a consultation on implementing a Geo-location based approach to enable white space access on a license-exempt basis in the UHF TV band [60], and consultation on white space device requirements [61].

2.3.3 Standardization Progress and Product Development of TV White Space

1) Standardization Progress

A number of standards groups have been developing standards for operation in the TVWS. Related standards are introduced in the following.

Cognitive Networking Alliance (CogNeA) is an open industry association aiming to help drive the definition and adoption of an industry-wide standard for low power personal and portable devices to operate over TVWS in UHF TV bands [62]. It is formed by a group of companies include Electronics and Telecommunications Research Institute (ETRI), HP, Philips, Samsung Electro-Mechanics, Texas Instruments, and British Telecom. The scope of this association is to promote the regulations on TVWS worldwide. CogNeA facilitates the compliance between cognitive devices from different manufacturers. In order to make CogNeA as an international standard, the association is in collaboration with Standards Definition Organization (SDO).

In March 2009, the alliance transferred the draft specification to European Computer Manufacturers Association International (Ecma), which was later published by the organization as Ecma-392 standard [63]. The Ecma-392 standard has a broad range of

applications including in-home high-definition multimedia networking and distribution, and internet access for communities.

The IEEE 802.22 standard is a standard for Wireless Regional Area Network (WRAN) using TVWS. It is the first wireless standard based on cognitive radios [49]. The 802.22 standard is designed to provide wireless broadband access services in large area (radius >30km), where less than 255 Consumer Premises Equipment (CPE) to be served per TV channel. The capacity of each WRAN CPE is expected to be 1.5 Mbps in downstream and 384 Kbps in upstream.

The IEEE 802.19 standard is focused on the development coexistence mechanisms amongst potentially dissimilar networks that operates in a common TVWS channel [64]. The 802.19 Working Group carries out the research on development of mechanisms for the discovery of other networks.

The IEEE 802.11af task group is under the IEEE 802.11 working group. It was established in 2009 to define a new standard to implement the use of a Wi-Fi technology within the TVWS, which is also called White-Fi [65].

The IEEE P1900.7 standard specifies radio interface including medium access control (MAC) layer and physical (PHY) layer of white space dynamic spectrum access radio systems supporting fixed and mobile operation in white space frequency bands, while avoiding causing harmful interference to incumbent users. The P1900.7 working group was setup in June 2011, and the standard aims to provide means to support P1900.4a for white space management and P1900.6 to obtain and exchange sensing related information (spectrum sensing and Geo-location information) [66].

The Internet Engineering Task Force (IETF) is a large open international community of network designers, operators, vendors, and researchers concerned with the evolution of the Internet architecture and the smooth operation of the Internet. The IETF working group “Protocol for Accessing TV White Space” (IETF PAWS) has a mandate to produce two deliverables that will specify the protocol that operates between a TVWS system and a database [67]. The first deliverable was finished in August 2012, and it contains relevant use cases and requirements for accessing a

radio white space database. The second deliverable was finished in April 2013, and it contains the specification of the mechanism for discovering and accessing a white space database, for example the query/response formats for interacting with a white space database [68].

Weightless is a standard for machine-to-machine (M2M) communications within white space spectrum [69]. It is developed by a special interest group and the main focus is providing low data rates at extended range with very low power battery consumption.

2) Product Development

In October 2012, the National Institute of Information and Communications Technology (NICT) in Japan has developed the world's first WiFi prototype in the TVWS based on the IEEE 802.11af draft specification. The developed system is the first prototype that verifies the physical and media access control layer design of the draft specification [70].

In January 2013, the National Institute of Information and Communications Technology (NICT) in Japan, Hitachi Kokusai Electric Inc. and ISB Corporation have developed the world's first prototypes of base station (BS) and consumer premise equipment (CPE) based on the IEEE 802.22 standard operating in TVWS frequency band, e.g. 470 MHz - 710 MHz. The developed prototypes provide broadband wireless access to under-served and un-served region, following the worldwide trend of promoting the TVWS for wireless communication systems [71].

In February 2013, Neul company announced that it is going to release the world's first TVWS transceiver chip. The new ASIC chip, Icen1, provides a low-power, low-cost, frequency-agile TVWS solution based on the Weightless standard. The chip is capable of being tuned across the entire TVWS band, and supports both 6 MHz and 8 MHz channel bandwidths [72].

2.3.4 Cognitive Access Methods to TV White Space

The successful operation of cognitive radio in TV bands relies on the ability of cognitive devices to detect TVWS without causing harmful interference to primary services, such as TV broadcasting and wireless microphones. Both FCC and Ofcom have considered three methods for spectrum detection as discussed in the following.

1) Beacons

The term beacon refers to non-visual radio signals for navigation and other purposes. As a spectrum sensing method, beacon means cognitive devices can transmit data only when they receive a control signal – beacon from a TV/FM broadcasting station, or a fixed unlicensed transmitter, indicating that there are vacant channels within their service areas. One problem with this method is that beacon infrastructure needs to be maintained, and the beacon signal may be lost due to the hidden terminal problem. Thus Ofcom has concluded in its statement that the beacon method is inferior to spectrum sensing and Geo-location database approaches, and not very suitable for cognitive radio [73].

2) Spectrum Sensing

With this method, cognitive devices autonomously detect the presence of TV signals and only use channels that are not used by TV stations. This sounds to be the most appropriate method, since it only utilizes the channels when they are detected as unoccupied without causing interference to primary use.

However, in reality the sensing method suffers the hidden terminal problem, as shown in Figure 2.7. This problem occurs when there is an obstacle between cognitive device and a TV station, while no obstacle between the TV station and primary user, the unlicensed device and the primary user. Hence, the cognitive device uses the occupied channel since it may not detect the TV signal from TV transmitter, which causes interference to the primary user.

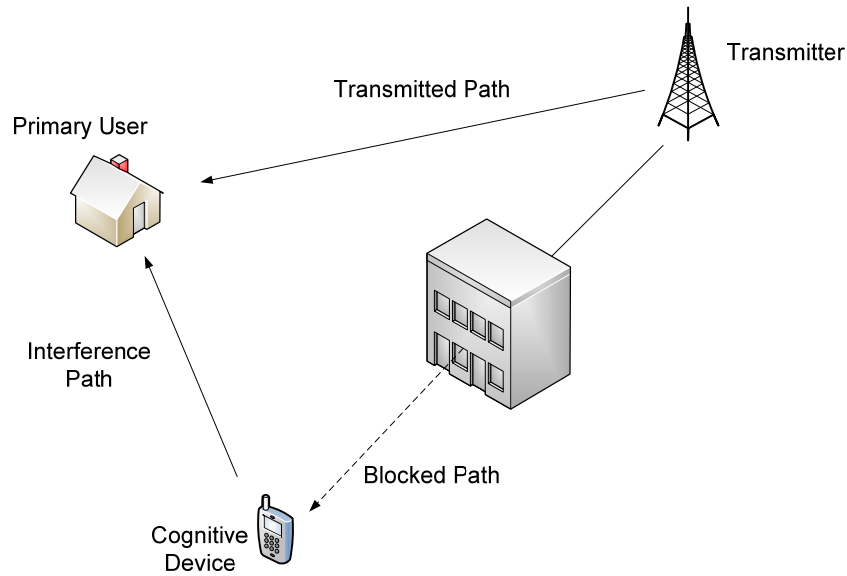


Figure 2.7 The hidden terminal problem illustration

In order to reduce the impact of hidden terminal problem, cognitive device needs to sense the TV signals down to a very low level, e.g. -114dBm for TV channels in US and -120dBm for TV channels in UK. However, it is very difficult in design and implementation to sense such weak signals that might be below the thermal noise. Even if it is possible to sense very low level, in the worst case, modelling work carried out by British Telecom [74] indicates that a cognitive device with sensing capability down to -114dBm may identify all TV channels as occupied, thus no TVWS is available for secondary users.

3) Geo-location Database

The Geo-location database method uses location database to determine the channels that can be used at that location and associated parameters, e.g. maximum transmit powers, for unlicensed users [75].

The operation of Geo-location database can be described as follows: there is a central Geo-location database holding the geographic locations of primary users and locations of unlicensed users. Based on this information the database can compute the protected service contour for each station, thus determining the available list of frequencies in a specific location. The database also computes possible signal strengths and the corresponding interference to incumbents, so as to determine the possible maximum transmit power for an unlicensed user requiring white space

access, under the condition that it must not cause harmful interference to the incumbents.

In order to implement Geo-location database method, there are at least three issues need to be considered. First, the database must be built and maintained by organizations or companies. Second, reliable location technology is required, since it is very important for the database to know the device locations with a certain accuracy. Third, device must be able to access the database via an always available channel in a different band before getting access to available TV channels.

Since the challenging design and implementation issues spectrum sensing method faces, the Geo-location database method is regarded as the most important mechanism for TVWS spectrum detection as suggested by Ofcom [9]. The Geo-location database method has drawn lots of attention and efforts from both academia and industry. In the EU Seventh Framework Programme, COGEU and QoS MOS projects have been working on developing TVWS Geo-location database prototypes [76][77].

By April 2013, in US there have been 3 companies, e.g. Spectrum Bridge, Telcordia, Google, which have done the trial on TV band database service. The trial's purpose is to ensure that the Geo-location database is functioning correctly and providing sufficient interference protection to the primary users according to FCC guidelines [78]. The Office of Engineering and Technology (OET) of the US has also announced that authorized database providers are able to operate on a nationwide [79].

Moreover, Google has announced a project to implement a TVWS trial network by utilizing Google's spectrum database solution in the Cape Town area of South Africa. This project aims to provide high-speed broadband service to a group of ten schools, and demonstrate that TVWS can be used to deliver affordable broadband services without interfering with TV reception [80].

2.3.5 Use Cases of TV White Space

The advantage of TVWS comes in the combination of capacity and coverage, which enables it to be used for various potential applications. Some use cases of TVWS are discussed in the following.

1) Machine-to-Machine (M2M) Communications

In M2M communications, devices which are similar or different connect to each other for information exchange in a peer-to-peer manner. There are a wide range of applications under this category, such as sensors, smart meters, healthcare, vehicles etc. The M2M communications require low cost hardware, low power consumption and excellent coverage. Because of its advantages of coverage and ubiquity, TVWS is regarded as a promising candidate spectrum for M2M communications [81].

2) Short Range Wireless Access Network

Short range wireless access points, such as home base stations (Femtocells) and Wi-Fi access points, can provide service to end users by using TVWS frequency bands. Femtocells are effective approach to enhancing indoor coverage and to providing capacity-demanding services. Current generation Femtocells use the same frequency band as mobile network, thus becoming a potential source of interference that are difficult to control. Cognitive radio based Femtocells operating in TVWS have the advantage of reduced or better controlled interference to the mobile network [82]. Backhauling Femtocells over TVWS is also of great interest to operators, it allows the mobile operator to get control of home base stations if customer-installed Femtocells are outside the DSL coverage or customer's broadband service is delivered by another operator.

A WLAN structure using cognitive radio over TVWS is proposed in [83]. The system consists of cognitive 802.11 access point (CAP) and multiple cognitive mobile stations (CMS). Geo-location method is applied for detecting primary service like DTV, assisted by spectrum sensing. In this structure, CAP performs spectrum sensing, look-up of the geo-location database, ranking available channels and channel switch decision making. CMSs are informed by CAP about the available usable channels and to switch to a new channel when interferer is detected on the active channel.

3) Wireless Regional Access Network (WRAN)

Wireless Regional Access Network is aiming to provide broadband access to hard-to-reach, low population density rural areas, using cognitive radio Technology to operate in the geographically unused TV broadcasting bands, while assuring no harmful interference to the primary service, such as TV broadcasting, wireless microphones [49]. Figure 2.8 shows the architecture of IEEE 802.22 network as an example of WRAN. The WRAN follows a point to multi-point layout. The network consists of base stations (BSs) and customer premises equipment (CPE). BSs are in charge of the medium access for all CPEs within its coverage, CPEs and BSs are connected via wireless links. The BSs and CPEs are capable of cognitive radio, and every CPE needs to detect all TV channels for vacant ones, then sends those channel information to BSs. Then BSs perform dynamic spectrum resource allocation to assign available channels to CPEs for wireless broadband access.

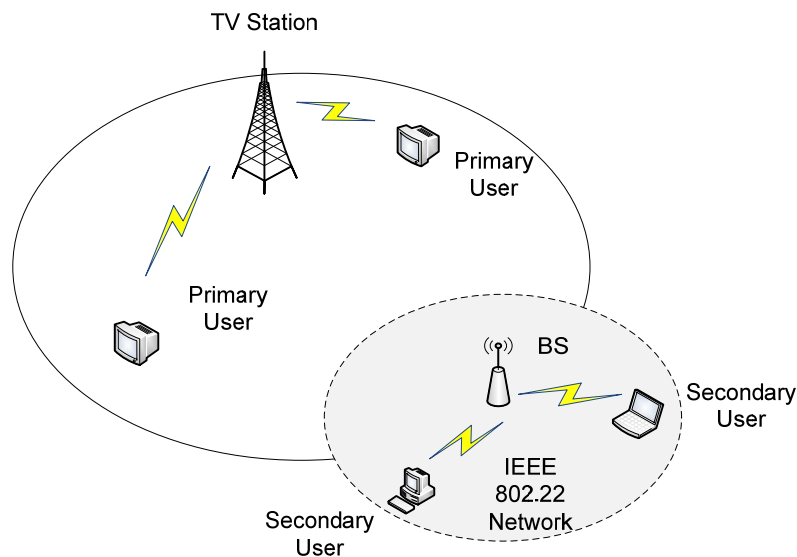


Figure 2.8 The architecture of an example WRAN

2.4 Constrained Nonlinear Optimization

In this thesis, sequential quadratic programming (SQP) method is used to solve the nonlinear constrained optimization problem formulated in Chapter 6. The related background is introduced in the following.

2.4.1 Constrained Nonlinear Optimization Problem

Nonlinear constrained optimization is the process of solving an optimization problem that is defined by a combination of objective function and constraint functions. Such optimization problems arise in a variety of applications in science, engineering, industry, and management.

The mathematical model of a nonlinear constrained optimization problem can be written in the form as: [84]

$$\min f(\mathbf{x}), \quad (2.1a)$$

$$\text{s.t. } \mathbf{g}(\mathbf{x}) \geq 0, \quad (2.1b)$$

where $\mathbf{x} = (x_1, x_2, \dots, x_n)^T \in R^n$, $f: R^n \rightarrow R$, $\mathbf{g}: R^n \rightarrow R^m$. $f(\mathbf{x})$ is a linear or nonlinear objective function, $\mathbf{g}(\mathbf{x}) = (g_1(\mathbf{x}), \dots, g_m(\mathbf{x}))^T$ is the set of nonlinear constraint functions.

A key function that plays a central role in constrained nonlinear optimization is the scalar-valued Lagrangian function. The Lagrangian function of Equation (2.1) is defined as [85]:

$$L(\mathbf{x}, \mathbf{v}) = f(\mathbf{x}) - \mathbf{v}^T \mathbf{g}(\mathbf{x}) \quad (2.2)$$

where $\mathbf{v} \in R^m$ is the Lagrangian multiplier vector.

The first order necessary optimality condition of nonlinear constrained optimization problem in Equation (2.1) is defined in Equation (2.3). Let $\mathbf{x}^* \in R^n$ be a local

minimum of the optimization problem in (2.1), and suppose there exists optimal Lagrange multiplier vector $\mathbf{v}^* \geq 0$ such that:

$$\nabla L(\mathbf{x}^*, \mathbf{v}^*) = \nabla f(\mathbf{x}^*) - \nabla \mathbf{g}(\mathbf{x}^*) \mathbf{v}^* = 0 \quad (2.3)$$

2.4.2 Sequential Quadratic Programming Method

One of the most powerful methods for solving smooth constrained nonlinear optimization problems is sequential quadratic programming (SQP) method. The SQP method is firstly proposed in Wilson's PhD thesis in 1963 [86], and becomes popular during the late 70's due to papers of Han [87] and Powell [88]. Many modifications and extensions on SQP method have been made since then.

The basic idea of SQP method is to formulate and solve a quadratic programming sub-problem in each iteration, which is obtained by linearizing the constraints and approximating the Lagrangian function of the original optimization problem [89]. A quadratic sub-problem is a problem with quadratic objective function and linear constraints. The quadratic problem is relatively easy to solve and can reflect the nonlinearities of the original problem.

The SQP method starts from any $\mathbf{x}_0 \in R^n$, suppose that in k_{th} iteration, $\mathbf{x}_k \in R^n$ is an approximation solution, $\mathbf{v}_k \in R^m$ is an approximation of the multipliers, and $\mathbf{H}_k \in R^{n \times n}$ is an approximation of the Hessian of the Lagrangian function. Thus, a quadratic programming sub-problem of Equation (2.2) can be formulated in the form in Equation (2.4).

$$\text{Minimize} \quad \frac{1}{2} \mathbf{d}^T \mathbf{H}_k \mathbf{d} + \nabla f(\mathbf{x}_k)^T \mathbf{d} \quad (2.4a)$$

$$\mathbf{d} \in R^n: \quad \nabla \mathbf{g}(\mathbf{x}_k)^T \mathbf{d} + \mathbf{g}(\mathbf{x}_k) \geq 0 \quad (2.4b)$$

This sub-problem is solved in each iteration, and merit function is used to guarantee the iteration process is in the direction towards convergence. Let \mathbf{d}_k be the optimal solution of (2.4), \mathbf{u}_k is the corresponding Lagrangian multiplier of this sub-problem.

The next iteration of the SQP method can be obtained by the following updating process:

$$\mathbf{x}_{k+1} = \mathbf{x}_k + \mathbf{d}_k \quad (2.5a)$$

$$\mathbf{v}_{k+1} = \mathbf{u}_k \quad (2.5b)$$

This process is iterated until the convergence criteria are met. Therefore, the constrained nonlinear optimization problem is solved and the solution points are obtained.

2.5 Summary

This chapter firstly presented the background of Femtocell networks. The existing approaches on solving downlink interference scenarios in Femtocell networks were discussed. These approaches are generally based on the licensed cellular frequency band, and have low spectrum efficiency when Macrocell and Femtocell share the spectrum. Then TVWS was discussed in this chapter, which is a newly opened portion of spectrum from digital switchover, and has been proposed by regulatory bodies for licence-exempting use based on cognitive radio technology. Among many use cases, TVWS could be a good candidate spectrum to be used by Femtocell networks with the aid of appropriate cognitive access method to solve the interference problem. Finally, constrained nonlinear optimization problem was discussed. The optimization problem is normally non-convex, and using Lagrangian multipliers method followed by KKT conditions will results in an NP-hard problem. SQP as an iterative approach is an effective method to solve the optimization problem, and is widely used in academia and industry in solving highly complex application problems. The overall discussions in this chapter laid the foundations for the research in this thesis.

Chapter 3 Simulation Scenarios and

Simulators

3.1 Introduction

This chapter introduces the design of two simulators that are used in the rest of the thesis. Firstly, the simulator for simplified Femtocell networks is introduced, which is used in Chapter 4 for demonstrating the system capacity improvement of simplified Femtocell networks using TVWS. Then, the simulator for two-tier OFDMA Femtocell networks is introduced, in which two Femtocell deployment scenarios are implemented for suburban Femtocell deployment and dense Femtocell deployment respectively. This simulator is used in Chapter 5 and 6 for demonstrating the performance of the proposed schemes for cross-tier interference and co-tier interference mitigation, respectively.

3.2 Introduction to the Research Approach

The research in this thesis aims at utilizing TVWS for cross-tier interference and co-tier interference mitigation in Femtocell networks. Following the research objective, firstly a power-control Geo-location database model to obtain locally available TVWS information was developed as a cognitive access method to TVWS. Based on the available TVWS information, a grid-based plus interference avoidance resource allocation scheme is proposed for a simplified Femtocell network scenario to investigate the system performance of using TVWS in Femtocell networks. In the proposed scheme, Femto BSs are assigned with associated available TVWS channels based on their grid locations. Secondly, a resource allocation scheme using locally available TVWS is proposed to mitigate the downlink cross-tier interference in suburban Femtocell deployment scenario. In this scheme, potential interfering Femtocells are identified and temporarily allocated with available TVWS spectrum

resource. Thirdly, a power efficient resource allocation scheme is proposed for co-tier interference mitigation in dense Femtocell deployment scenario. In this scheme, power allocations on sub-channels are adjusted according to the solution of the constructed power allocation optimization problem by using SQP method, so that to maximize the system throughput while limiting the co-tier interference among Femtocells. The simulators used for different Femtocell network scenarios mentioned above are introduced in the following sections.

3.3 Simulator for Simplified Femtocell Networks

3.3.1 Simulation Scenario

As shown in Figure 3.1, the simulated simplified Femtocell network is a single Macrocell network with several Femtocells located randomly within it to represent an actual Femtocell deployment distribution. There are two categories of users: 1) Femto UEs being served by Femto BSs; and 2) Macro UEs being served directly by a Macro BS.

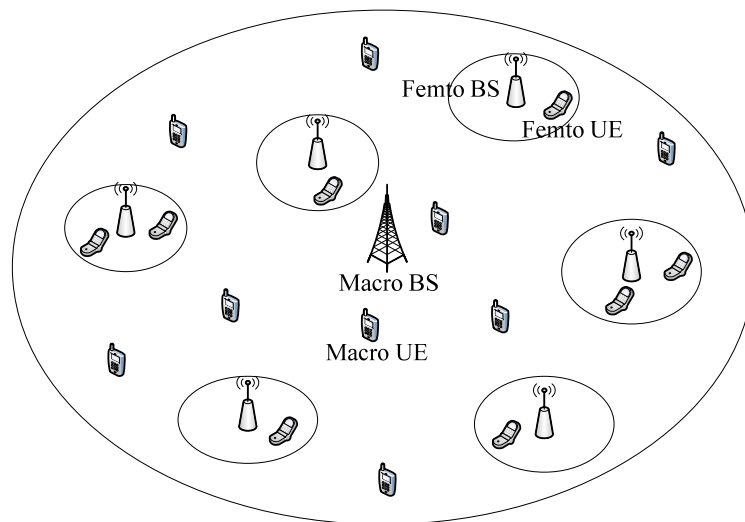


Figure 3.1 Illustration of simplified Femtocell networks

3.3.2 Module Description

The flow chart of the simulator for simplified Femtocell networks is illustrated in Figure 3.2. Each module is described as follows:

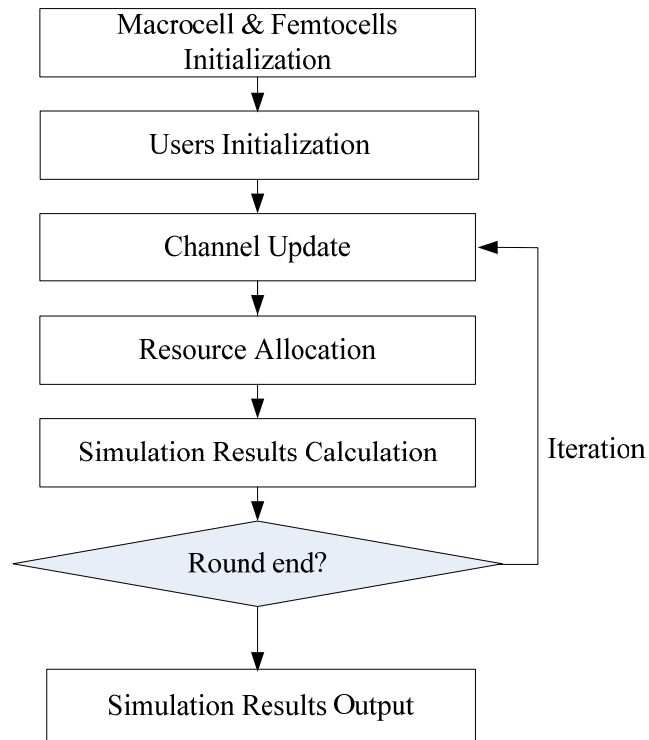


Figure 3.2 Flow chart of the simulator for simplified Femtocell networks

1) Macrocell and Femtocells Initialization

Create Macrocell and Femtocells, Femtocells are randomly located with uniform distribution in the Macrocell coverage area.

2) Users Initialization

Create Macro and Femto UEs, which are randomly located with uniform distribution in Macrocell and Femtocells respectively.

3) Channel Update

Update the path loss for each Macro and Femto UE according to corresponding channel models.

4) Resource Allocation

Perform the proposed resource allocate scheme.

5) Simulation Results Calculation

Based on users' received signal power, bandwidth and noise, calculate system capacity.

6) Simulation Results Output

Based on data obtained, save the simulation results and output diagrams.

3.3.3 Channel Model

In the simplified Femtocell networks simulator, transmission path loss is considered in the channel model. The path loss for Macro and Femto UEs is modelled according to the IMT-2000 channel model [90]. The applicable frequency range of this model is 150kHz to 2000MHz, thus it can be used for modelling path loss of signals in mobile spectrum band and TV band as well.

1) Macro BS to Macro UEs:

$$PL_{dB}^M = A_{dB} + 10\alpha \log_{10} R \quad (3.1)$$

where α is the outdoor path loss exponent. The normal value of α is 3.8. $A_{dB} = 30 \log_{10} f_c - 71$ represents the fixed decibel loss during outdoor propagation, where f_c is the carrier frequency in MHz and R is the distance in m.

2) Femto BS to Femto UEs:

$$PL_{dB}^F = A_{f,dB} + 10\alpha_f \log_{10}(R_f) \quad (3.2)$$

where $A_{f,dB} = 37\text{dB}$ models the fixed propagation loss in decibels between the Femtocell to its desired user. α_f represents the indoor path loss exponent, and the normal value is 3.

3.3.4 Simulation Parameters

In the simulator for simplified Femtocell networks, simulation parameters are shown in Table 3.1.

Table 3.1 Simulation parameters for simplified Femtocell networks simulator

Parameter	Assumption
Rc: Marocell radius	1000m
Rf: Femtocell radius	30m
Nt: No. of total user	100
Nf: No. of Femtocells per Macrocell	10, 20, 30
Nfu: No.of Femto UEs per Femtocell	2
Nm: No. of Macro UEs	80,60,40
Pc: Maximum Transmit Power at Macro BS	43dBm
Pf: Maximum Transmit Power at Femto BS	23dBm
BWuser: Bandwidth for each user	200kHz
Nt: Thermal Noise	-106.2dBm

3.4 Simulator for OFDMA Femtocell Networks

The OFDMA Femtocell networks simulator is designed with two Femtocell deployment scenarios, which are suburban Femtocell deployment and dense Femtocell deployment respectively.

3.4.1 Simulation Scenarios

1) Suburban Deployment Scenario

As shown in Figure 3.3, in this scenario each Femto BS is modelled as a (2 dimensional) rectangular house with surrounding space according to the suburban modelling in 3GPP specifications on HeNB simulation [91]. In the Macro BS coverage area, Macro UEs, Femto BSs and Femto UEs randomly located with uniform distribution. Femto BSs are randomly dropped within the Macrocell area, subject to minimum separation to the Macro BS. The density of Femto BSs per Macrocell is a variable in the simulations. Each of the dropped Femto BS is assumed to be “active”, which means there is at least one active call. Within each house the Femto BS and Femto UEs are dropped randomly within a certain distance of the centre of the houses. A Macro UE may be within a house as well.

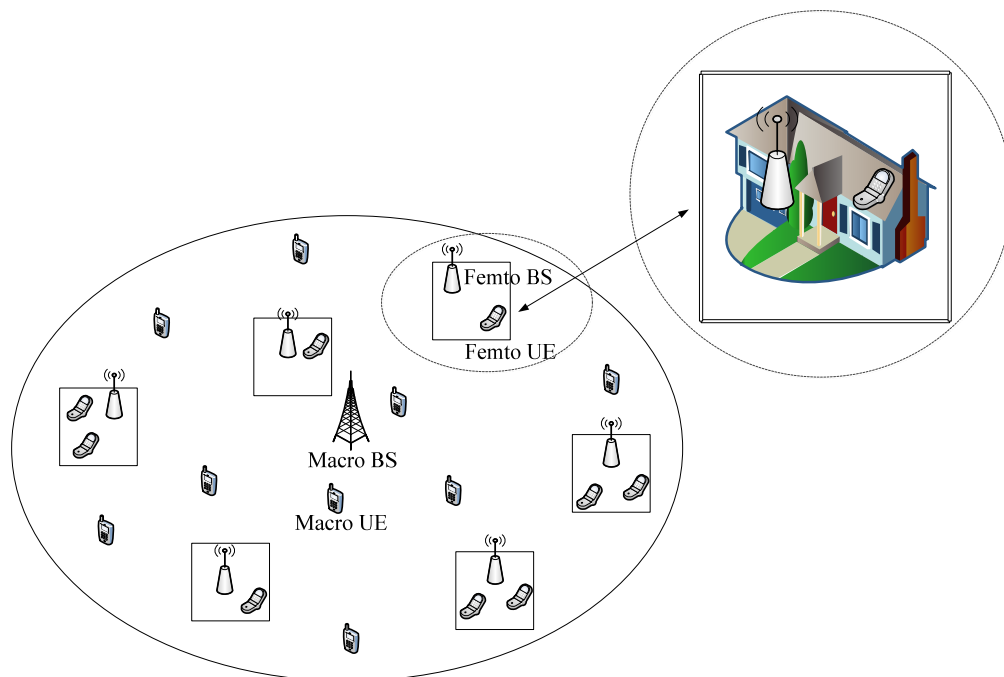


Figure 3.3 Illustration of suburban Femtocell deployment scenario

2) Dense Deployment Scenario

In a city urban area, Femtocells are often installed in apartments in building blocks to provide better indoor coverage, which often forms a dense Femtocell deployment, as illustrated in Figure 3.4. In this scenario, Femtocells can be deployed in very close proximity in apartments. A dual strip model from 3GPP specifications on HeNB simulation is adopted for modelling dense Femtocell deployment [91]. As illustrated in Figure 3.4, in this model, each Femtocell block represents two stripes of apartments; each stripe has 2 by N apartments. In each Macrocell area, one or several Femtocell blocks are randomly dropped. It is assumed that the Femtocell blocks are not overlapping with each other. Each Femtocell block has L floors, and the floor number is chosen between 1 and 10. Each Femtocell block has L floors, and the floor number is chosen between 1 and 10.

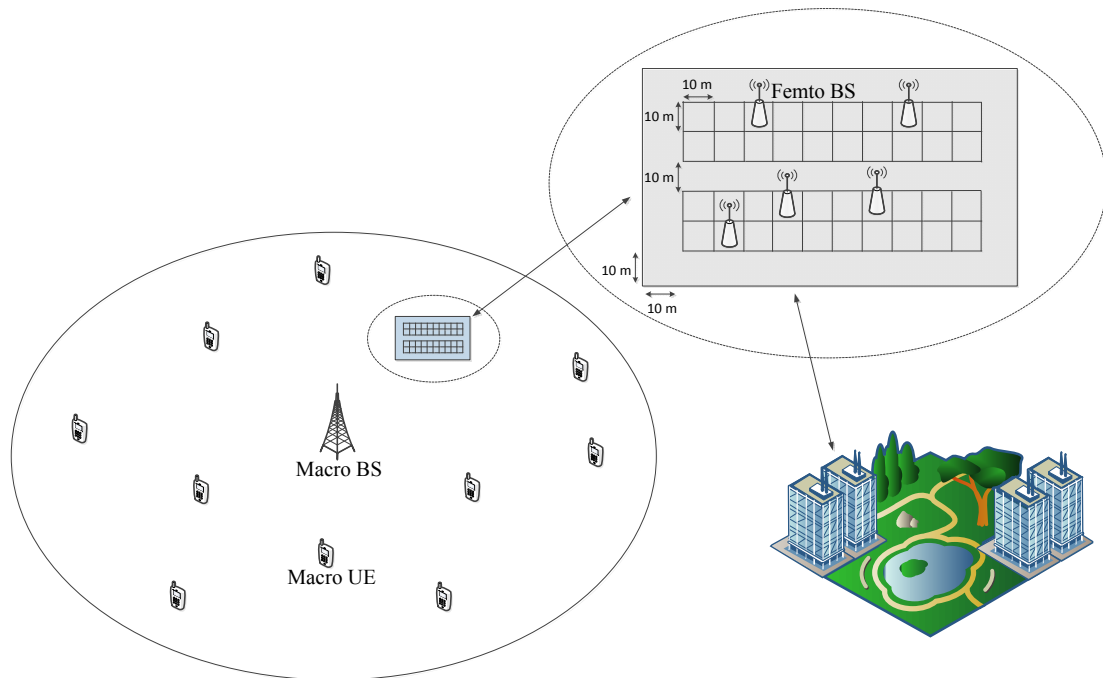


Figure 3.4 Illustration of dense Femtocell deployment scenario

3.4.2 Module Description

The flow chart of the simulator for OFDMA Femtocell networks is illustrated in Figure 3.5. Each module is described as follows:

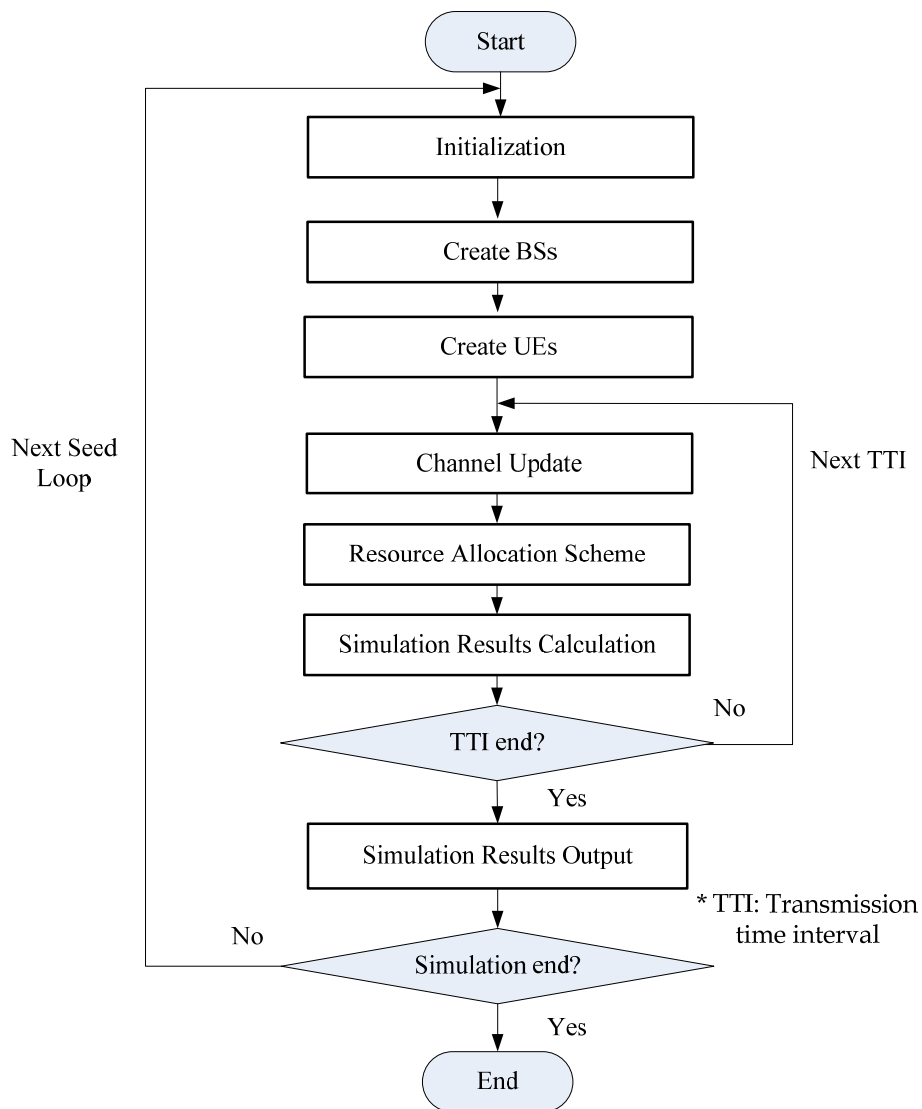


Figure 3.5 Flow chart of the simulator for OFDMA Femtocell networks

1) Initialization

Set the parameters used for simulator initialization including:

- Macro BS parameters: radius, transmit power;
- Femto BS parameters: radius, transmit power;
- OFDMA sub-channel parameters: total bandwidth, number of sub-channels;

- Femtocell deployment parameters: Femtocell deployment ratio and activation ratio;
- Other simulation parameters: number of Femto BSs, number of Femto UEs and Macro UEs.

2) Create BSs

Create Femto BSs that are randomly located in the Macrocell area with uniform distribution, ensuring no overlap between Femto BSs and a minimum distance from Macro BS.

3) Create UEs

Create Macro UEs and Femto UEs which are randomly located with uniform distribution in Macrocell and houses or apartments respectively, ensuring the minimum distances from Macro UEs to Macro BS and from Femto UEs to Femto BSs.

4) Channel Update

Update the path loss and shadowing fading for Macro and Femto UEs according to corresponding channel models.

5) Resource Allocation Scheme

The proposed and comparison resource allocation schemes are implemented in this step.

6) Simulation Results Calculation

Based on the UEs' received signal power, bandwidth and the noise, calculate the UEs Interference, SINR, throughput, and power consumption.

7) Simulation Results Output

Based on data obtained from results calculation, save the simulation results and output diagrams.

3.4.3 Channel Model

In the OFDMA Femtocell Networks simulator, the path loss models in different deployment scenarios and shadowing model are built according to the corresponding model in 3GPP specifications on HeNB simulation [91]. The applicable frequency range of this model is 300MHz to 5 GHz, thus it can be used for modelling path loss of signals in mobile spectrum band and TV band as well.

1) Suburban Deployment Scenario

A. Macro BS to UE

- i. UE is outside a house

$$PL(dB) = 15.3 + 37.6\log_{10}R \quad (3.3)$$

- ii. UE is inside a house

$$PL(dB) = 15.3 + 37.6\log_{10}R + L_{ow} \quad (3.4)$$

B. Femto BS to UE

- i. UE is inside the same house as Femto BS

$$PL(dB) = 38.46 + 20\log_{10}R + 0.7d_{2D,indoor} \quad (3.5)$$

$$+ 18.3n^{\left(\frac{n+2}{n+1}-0.46\right)}$$

- ii. UE is outside a house

$$PL(dB) = \max(15.3 + 37.6\log_{10}R, 38.46 + 20\log_{10}R) \quad (3.6)$$

$$+ 0.7d_{2D,indoor} + 18.3n^{\left(\frac{n+2}{n+1}-0.46\right)} + L_{ow}$$

- iii. UE is inside a different house

$$PL(dB) = \max(15.3 + 37.6\log_{10}R, 38.46 + 20\log_{10}R) \quad (3.7)$$

$$+ 0.7d_{2D,indoor} + 18.3n^{\left(\frac{n+2}{n+1}-0.46\right)} + L_{ow,1} + L_{ow,2}$$

where R is the transmitter and receiver separation in meters, L_{ow} is the penetration loss of an outdoor wall, which is 10dB or 20dB. n is the number of penetrated floors. In (3.6) $d_{2D,indoor}$ is the distance inside the house in meters. In (3.7) $d_{2D,indoor}$ is the total distance inside the two houses. $L_{ow,1}$ and $L_{ow,2}$ are the penetration losses of outdoor walls for the two houses.

2) Dense Femtocell Deployment Scenario

A. Macro BS to UE

i. UE is outside

$$PL(dB) = 15.3 + 37.6\log_{10}R \quad (3.8)$$

ii. UE is inside an apartment

$$PL(dB) = 15.3 + 37.6\log_{10}R + L_{ow} \quad (3.9)$$

B. Femto BS to UE

i. UE is inside the same apartment stripe as Femto BS

$$PL(dB) = 38.46 + 20\log_{10}R + 0.7d_{2D,indoor} \quad (3.10)$$

$$+ 18.3n^{\left(\frac{n+2}{n+1}-0.46\right)} + q \times L_{iw}$$

ii. UE is outside the apartment stripe

$$PL(dB) = \max(15.3 + 37.6\log_{10}R, 38.46 + 20\log_{10}R) \quad (3.11)$$

$$+ 0.7d_{2D,indoor} + 18.3n^{\left(\frac{n+2}{n+1}-0.46\right)} + q \times L_{iw} + L_{ow}$$

iii. UE is inside a different apartment stripe

$$PL(dB) = \max(15.3 + 37.6\log_{10}R, 38.46 + 20\log_{10}R) \quad (3.12)$$

$$+ 0.7d_{2D,indoor} + 18.3n^{\left(\frac{n+2}{n+1}-0.46\right)} + q \times L_{iw} + L_{ow,1} + L_{ow,2}$$

where R is the transmitter and receiver separation in meters, L_{ow} is the penetration loss of an outdoor wall, which is 10dB or 20dB. The term $0.7d_{2D,indoor}$ takes account of penetration loss due to walls inside an apartment. n is the number of penetrated floors. q is the number of walls separating apartments between UE and Femto BS. L_{iw} is the penetration loss of the wall separating apartments, which is 5dB. In case of a single-floor apartment, the term $q \times L_{iw}$ is not needed.

3) Shadowing Models

In both suburban and dense deployment simulation scenarios, log-normal shadowing applies to all transmission links. For links between a Femto BS and a UE served by this Femto BS, the standard deviation is assumed to be 4dB; otherwise, for all other links (including interference links) the standard deviation is 8dB [91].

3.4.4 Simulation Parameters

1) Suburban Deployment Scenario

The simulation parameters of designed OFDMA Femtocell networks simulator in suburban deployment scenario are listed in Table 3.2.

Table 3.2 Simulation parameters of OFDMA Femtocell networks simulator in suburban deployment scenario

Parameter	Assumption
Femtocells per Macrocell	10
Femto UEs per Femtocell	2
Number of Macro UEs	50
Macrocell Radius	288m
Femtocell Radius	12m
Wall Penetration Loss	10dB/20dB
System Bandwidth	10MHz
Total No. of Sub-channels	50
Sub-channel Bandwidth	180kHz
Macro BS Transmit Power	46dBm
Femto BS Transmit Power	20dBm
Thermal Noise	-174dBm/Hz
Minimum Distance between UE and Macro BS	35m
Minimum Separation between UE and Femto BS	20cm

2) Dense Femtocell Deployment Scenario

The simulation parameters of the designed OFDMA Femtocell networks simulator in dense Femtocell deployment scenario are listed in Table 3.3.

Table 3.3 Simulation parameters of OFDMA Femtocell networks simulator in dense Femtocell deployment scenario

Parameter	Assumption
Femtocell block per Macrocell	1
Macrocell Radius	288m
Femtocell Radius	12m
Wall Penetration Loss	10dB/20dB
System Bandwidth	5MHz
Total No. of Sub-channels	25
Sub-channel Bandwidth	180kHz
Macro BS Transmit Power	46dBm
Femto BS Transmit Power	20dBm
Thermal Noise	-174dBm/Hz
N (number of cells per row)	10
L (number of floors per block)	10
R (Femtocell deployment ratio)	0.25
P (Femtocell activation ratio)	50%
Minimum Distance between UE and Macro BS	35m
Minimum Separation between UE and Femto BS	20cm

3.5 Simulation Validation

As the credibility of simulators is important groundwork of research, the simulation codes of simulator used in this research have been debugged line by line with the aid of breakpoints.

Figure 3.6 evaluates the effect of number of simulation iterations in the OFDMA Femtocell network simulator. The vertical axis indicates the average Femto UE total throughput of corresponding simulation iterations, while the horizontal axis indicates the number of simulation iterations. As we can see from the diagram, with the increase of the number of iterations, the data gradually approaches 1.015789×10^8 (indicated by the black line), which is the average value of Femto UE total throughput of 800 simulation iterations. Therefore, the simulation results are well converged after 800 simulation iterations.

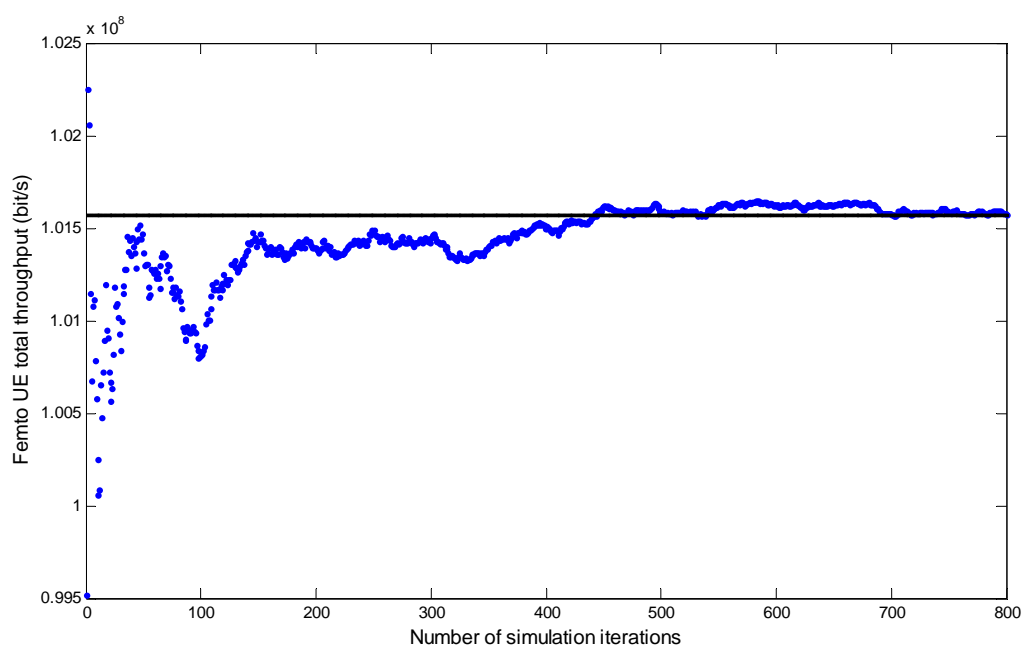


Figure 3.6 Femto UE total throughput vs number of simulation iterations

Figure 3.7 shows the distribution of path loss from serving Femto BS to Femto UE in the OFDMA Femtocell network simulator. In this experiment, Femto UEs and Femto BSs are dropped in the simulation area randomly with uniform distribution, and path loss from every Femto BS to every Femto UE is computed. This process is repeated 800 times, and then the CDF diagram of all path loss samples is plotted. The

resulted CDF curve complies with the path loss model evaluation result shown in 3GPP specifications on HeNB simulation [91][92]. This demonstrates that the path loss model in the simulator is implemented correctly.

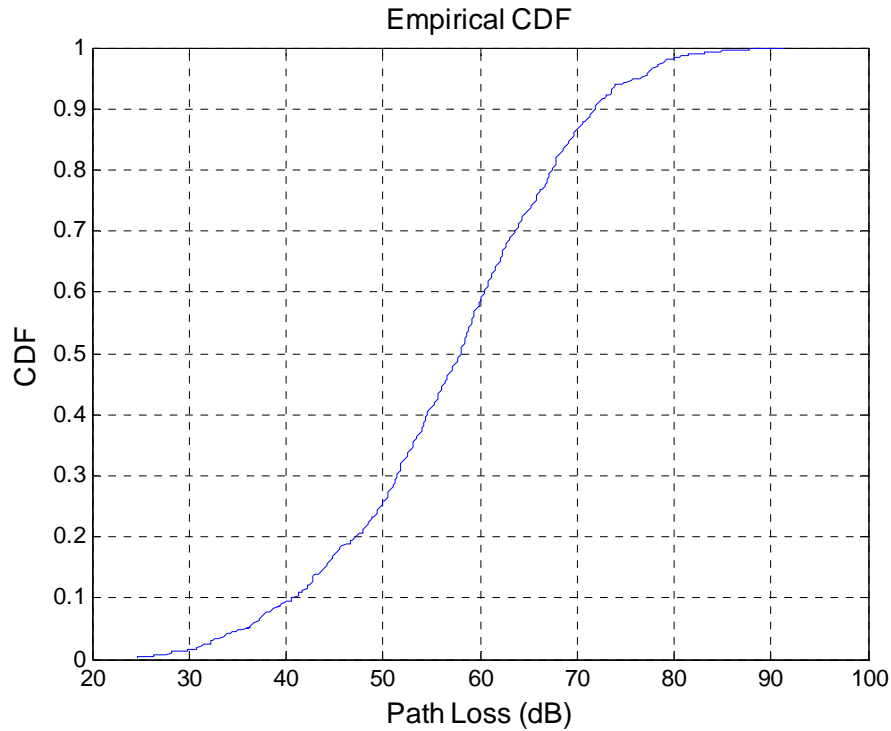


Figure 3.7 Distribution of path loss from serving Femto BS to Femto UE

3.6 Summary

In this chapter, the simplified Femtocell networks simulator was designed, which will be used in Chapter 4. Then the two-tier OFDMA Femtocell networks simulator with two deployment scenarios were established, which will be used in Chapter 5 and 6, respectively. Simulation scenarios, flow charts, and module descriptions of the two simulators were logically presented. Channel models and simulation parameters used in the simulators have been set up according to 3GPP specifications on HeNB simulation. The simulators introduced in this chapter will be used in the research of following chapters.

Chapter 4 Design of TV White Space for Simplified Femtocell Networks

4.1 Introduction

Regulatory bodies, e.g. FCC and Ofcom, have opened the way to reuse TVWS under strict limitations. There are many potential use cases of TVWS being envisioned. This research proposes to use TVWS in Femtocell networks, so that Femtocell can bring the capacity enhancement without causing interference due to the shared use of mobile spectrum with traditional Macrocell networks. In this chapter, firstly a Geo-location database model is designed as a cognitive access method to obtain locally available TVWS information. Then, based on the available TVWS, a grid-based plus interference avoidance resource allocation scheme is proposed for a simplified Femtocell network to investigate the system performance of using TVWS in Femtocell networks.

4.2 Simplified Femtocell Networks

Femtocell is an effective approach to increase the system capacity in cellular networks. It is a home base station with short range, low cost and low power, installed by consumer for better indoor reception. In traditional Femtocell networks, since Femtocell uses the same frequency band as the Macrocell network, adding of Femtocells may create interference between Femtocells and Macrocell, thus decreasing the system performance. In this research, the use of TVWS spectrum for Femtocell networks is proposed to enhance network capacity without causing interference which is normally generated by the shared use of mobile spectrum with traditional Macrocell networks.

The simplified Femtocell networks serve as the research scenario in this chapter to investigate the system capacity performance when adding Femtocells that are using

TVWS. As shown in Figure 4.1, the research scenario is a single Macrocell network, where several Femtocells randomly located with uniform distribution. This represents a traditional Femtocell deployment. There are two categories of users: 1) Femto UE which is served by Femto BS; and 2) Macro UE which is served directly by Macro BS.

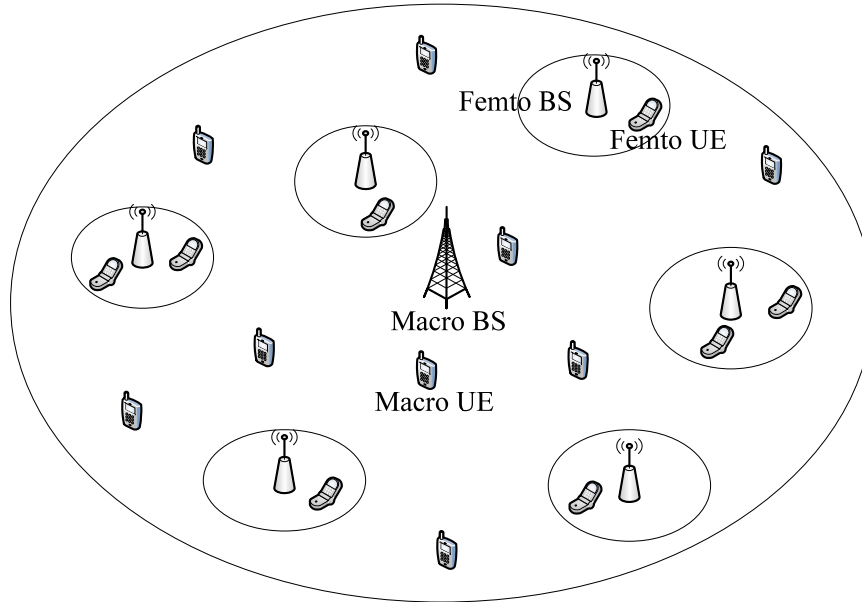


Figure 4.1 Illustration of simplified Femtocell networks scenario

4.3 The Proposed Geo-location Database Model

In order to utilize the TVWS for Femtocell networks, the knowledge of local TVWS information is crucial, e.g. available TVWS channels and associated maximum transmit power. As discussed in section 2.3.4, the Geo-location database method is regarded as the most promising method for TVWS spectrum detection as suggested by Ofcom [9]. In this section, a power-control Geo-location database model is designed to obtain locally available TVWS information and protect the primary TV system from harmful interference. The results of Geo-location database model are verified as well.

4.3.1 The Keep-away Region Geo-location Database Model

A Keep-away region Geo-location database model is introduced in [93]. This model introduced a concept called “keep-away distance”, which indicates the minimum safe distance that a CR station which intends to use TVWS should keep away from the edge of DTV coverage, so as to avoid causing harmful interference to DTV users. The keep-away distance is calculated by the function of the transmit power of DTV and CR stations and the acceptable Signal to Interference Ratio (SIR) of DTV users at the coverage edge. If a CR station is outside a DTV station’s keep-away region, then it can reuse the operational TV channels of that DTV station as TVWS. An illustrative example of this database model is shown in Figure 4.2. There are two DTV stations and a CR station. The green lines indicate the coverage edge of DTV station, and red lines indicate the keep-away region contour. In this case, DTV station 1 operates in TV channels 22, 26, 39, while DTV station 2 operates in TV channels 25, 28, 40. Thus, a CR station can reuse the TV channels 22, 25, 26, 28, 39, 40 as TVWS, if it is located outside the keep-away region of these two DTV stations. Therefore, for a specific location of CR station the keep-away region Geo-location database model can calculate and return the available TVWS channels to that CR station.

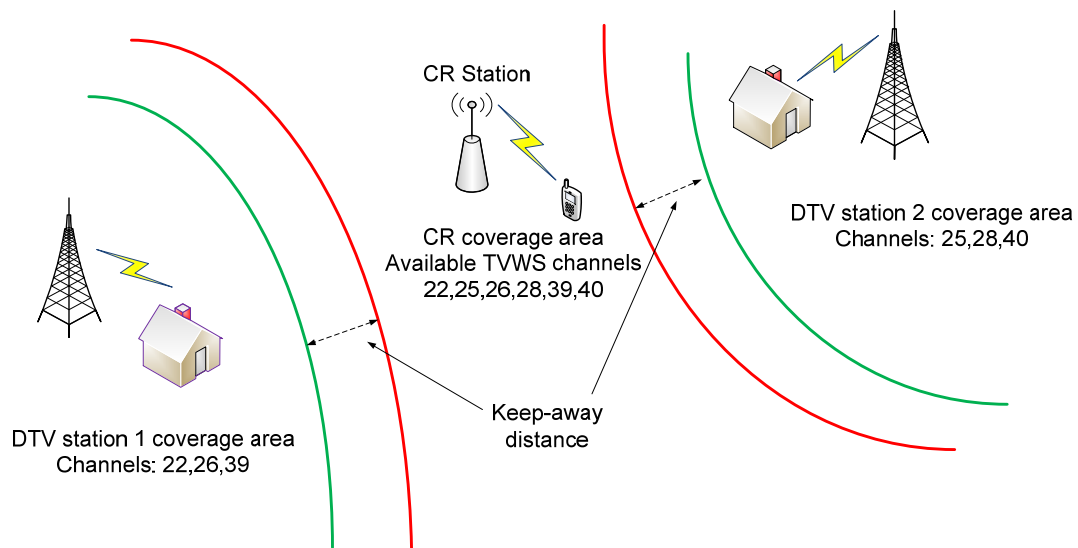


Figure 4.2 Illustration of the keep-away region Geo-location database model

4.3.2 The Proposed Power-control Geo-location Database Model

The keep-away region model assumes that there is no power control strategies built in CR stations. The transmit power of CR stations is fixed. However, it would be more efficient to use the TVWS spectrum if a power control strategy is adopted to dynamically determine the possible maximum transmit power for CR stations, under the condition that not exceeding the interference protection ratios required by DTV users. Therefore, a power-control Geo-location database model is proposed in this thesis.

An illustrative example of the proposed power-control Geo-location is shown in Figure 4.3. There are two DTV stations and a CR station. The green lines indicate the coverage edge of DTV station. By using the proposed power-control Geo-location database model, the CR station can obtain the available TVWS channels at its location and the associated maximum transmit power for each TVWS channel as well. Moreover, the CR station that wants to reuse the TV channels as TVWS don't have to be located outside a certain distance from the DTV coverage edge, which is required by the keep-away region Geo-location database model. Thus, the TVWS spectrum can be used more efficiently.

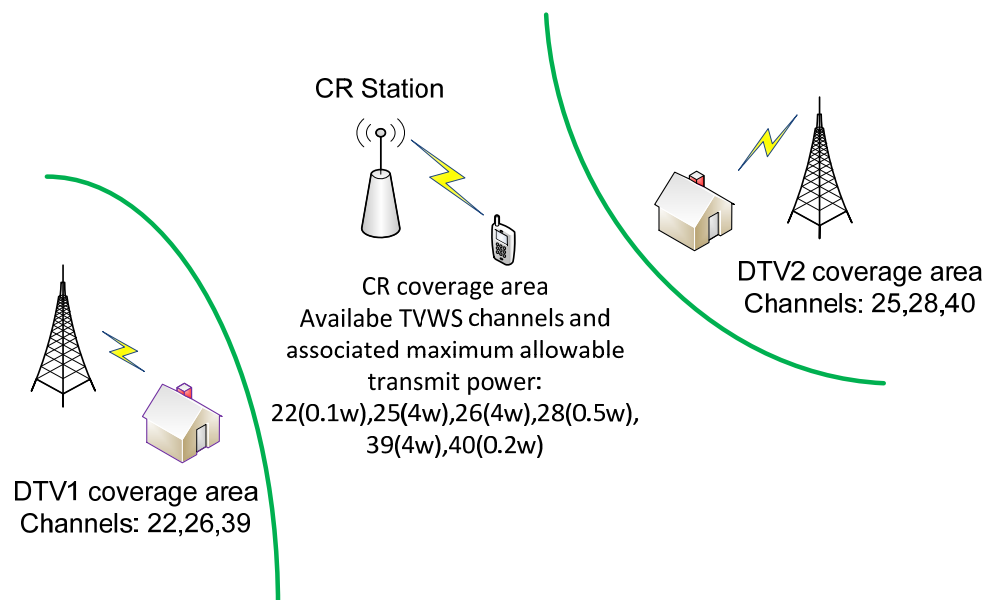


Figure 4.3 Illustration of the power-control Geo-location database model

Next, the proposed power-control Geo-location database model is described in three aspects: 1) establishing the DTV station database; 2) calculation of available TVWS channels; and 3) calculation of associated maximum transmit power.

1) Establishing the DTV Station Database

The DTV station database used in the proposed power-control Geo-location database model is set up according to the “Digital Switchover Transmitter Details” published by Ofcom [94], as shown in Table 4.1. The DTV station database is established including following information for each DTV station: DTV station location, operational channels, transmit power and radius of coverage.

Table 4.1 Part of the DTV Switchover Transmitter Details (DTV transmitters information in London area) [94]

Site Name (Region)	National Grid Reference (NGR)	PSB Multiplexes			COM Multiplexes			ERP (kW)	Aerial Group
London									
Crystal Palace	TQ339712	23	26	30	22	25	28	200	AH
Guildford	SU974486	43	46	49	48	52	56	2	EV
Hemel Hempstead	TL087044	41	44	47	55	59	62	2	EV
Reigate	TQ256521	53	7	60	21	24	27	2	WV

2) Calculation of Available TVWS Channels

Given location information of a CR station, the proposed database model calculates all the distances from the CR station location to the coverage edge of all 81 DTV stations in UK. The model checks whether each distance is greater than a minimum distance threshold $d_{min_threshold}$. This threshold is defined as the minimum distance to a DTV coverage edge, within which no secondary transmission would be allowed (typically 100m) [95]. If the distance from the CR station to a DTV station coverage edge is greater than the $d_{min_threshold}$, the operational channels of that DTV station are tagged as *vacant* and put into a white list, otherwise the operational channels are tagged as *occupied*, and put into a black list. This procedure is repeated for each DTV station.

Moreover, there is a case that a number of different DTV stations in different places share the same channel. In other words, the same channel may appear in both of the

black and white lists. Therefore, in order to avoid the collision of TV channels, a further comparison between white list and black list is made. Channels in both black and white lists are deleted from the white list. At last, a list of available TVWS channels for the given CR station location can be obtained.

3) Calculation of Associated Maximum Allowable Transmit Power

The proposed power-control Geo-location database model calculates the associated maximum allowable transmit power $EIRP_{max}$ of the CR station for each available TVWS channel.

According to the computationally simple but relatively accurate two-ray propagation model introduced in [96], the $EIRP_{max}$ can be calculated by Equation (4.1), where d is the distance between CR station and DTV station coverage edge, η is the intrinsic impedance. In order to obtain $EIRP_{max}$ in (4.1), $E_{Edge_{max}}$ should be calculated, which is the maximum allowable E-field strength of secondary use at the affected DTV station coverage edge, and d_{BP} , the "Break-Point Distance".

$$EIRP_{max} = \frac{4\pi d^4}{d_{BP}^2} \frac{E_{Edge_{max}}^2}{\eta} \quad (4.1)$$

$$E_{Edge_{max}} = E_{TV} - (D/U)_{cc} + F/B \quad (4.2)$$

$$d_{BP} = KH_{TX}H_{RX}/\lambda \quad (4.3)$$

$E_{Edge_{max}}$ can be calculated based on the required interference protection D/U ratios (Desired-to-Undesired signal levels) of TV service at the edge of DTV protected contour [97], as shown in Equation (4.2), where E_{TV} is the E-field strength of DTV signal at its protection contour, $(D/U)_{cc}$ is the maximum tolerable co-channel interference protection ratio for the affected service. F/B represents the 14dB front-to-back ratio for the affected TV receiver antenna.

The "Break-Point Distance" d_{BP} is used to differentiate the square-law and forth law for the two-ray propagation model, and can be calculated according to Equation (4.3), where K is a predefined constant ranging from 0.5 to 8, λ is the wavelength in meters, H_{TX} and H_{RX} are the heights of CR station transmit antenna and incumbent TV receiver antenna in meters, respectively.

At last, the obtained $EIRP_{max}$ is compared with the maximum allowable transmit power for fixed CR station using TVWS, which is 4W as defined in [97]. The final result of the maximum allowable transmit power for the available TVWS channel is the smaller one between the obtained $EIRP_{max}$ and the maximum power for fixed CR station using TVWS.

The flow chart of proposed power-control Geo-location database model is shown in Figure 4.4, where i is the TV station number, and there are total 81 TV stations in UK.

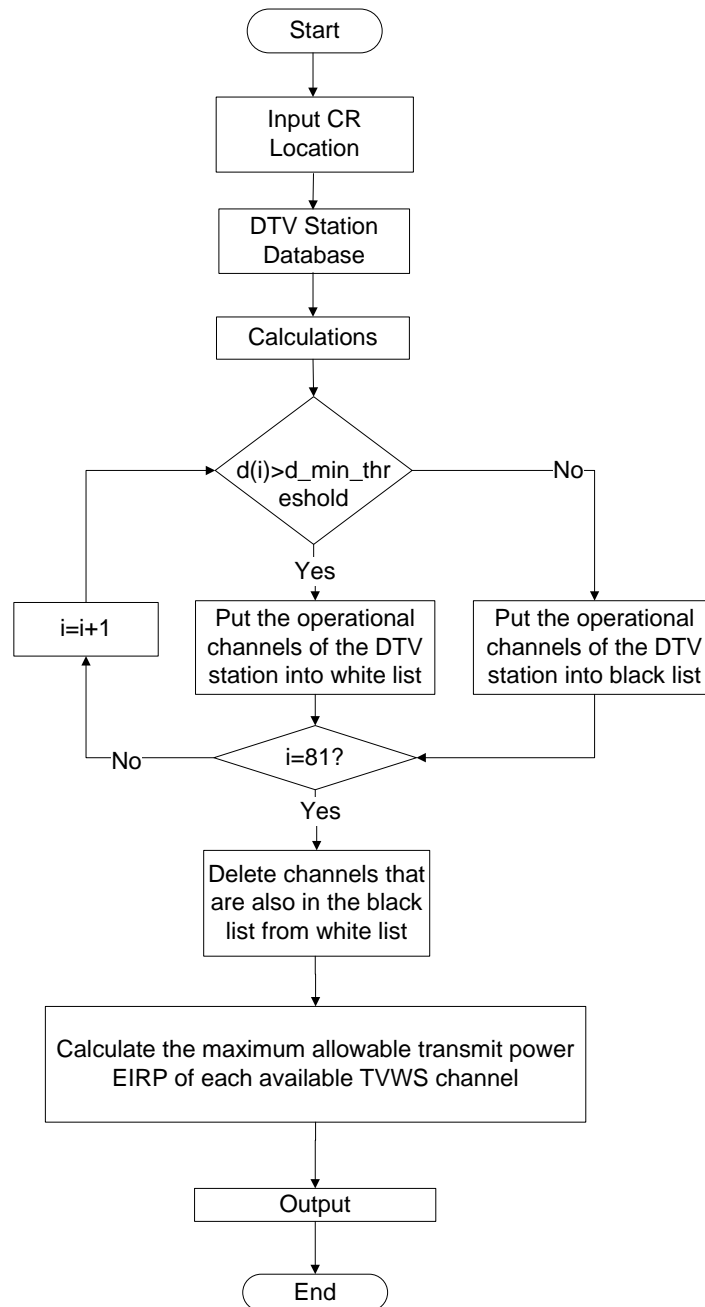


Figure 4.4 The flow chart of the proposed power-control Geo-location database model

4.3.3 Geo-location Database Results and Analysis

1) Comparing with the Keep-away Region Geo-location Database Model

In order to make a comparison between the proposed power-control Geo-location database model and the keep-away region model, 12 locations in UK are selected along with their NGR coordinates as shown in Table 4.2.

Table 4.2 List of 12 locations in UK

No.	Location	National Grid Reference (NGR)	No.	Location	National Grid Reference (NGR)
1	Glasgow	NS595655	7	Brighton	TQ315065
2	Southampton	SU425135	8	London	TQ315815
3	Bristol	ST065755	9	Birmingham	SP095875
4	Plymouth	SX475565	10	Edinburgh	NT275735
5	Cardiff	ST185765	11	Swansea	SS645945
6	Newcastle	NZ255645	12	Manchester	SJ835985

By inputting a location in Glasgow (National Grid Reference: NS595655), the results of available TVWS information of the proposed power-control Geo-location database model and the keep-away region model are presented in Table 4.3 and 4.4 respectively. The results include the available TVWS channel number and the associated maximum allowable transmit power EIRP.

Table 4.3 Available TVWS information in Glasgow by power-control model

Glasgow (NS595655)										
Channel No.	30	42	45	48	49	51	52	55	56	59
Max. EIRP (watts)	4	0.128	0.119	4	0.108	4	4	4	4	4

Table 4.4 Available TVWS information in Glasgow by keep-away region model

Glasgow (NS595655)							
Channel No.	30	48	51	52	55	56	59
Max. EIRP (watts)	4	4	4	4	4	4	4

As is shown in Table 4.3 and 4.4, both models return the available TVWS channels 30, 48, 51, 52, 55, 56, 59 with fixed maximum allowable EIRP 4W. Moreover, the proposed power-control database model returns more TVWS channels 42, 45, 49 with less maximum allowable EIRP. The results show that the proposed model can provide more TVWS channels to be used by CR stations, provided that they do not exceed the associated maximum allowable transmit power. This is especially beneficial to CR stations with small transmit power, for example, Femto BSs using TVWS. Therefore, compared with the keep-away region model the proposed power-control model is more efficient in terms of obtaining more available TVWS channels with flexible maximum allowable EIRP.

The 12 different locations in Table 4.2 are inputted to the two Geo-location database models. The corresponding results of available TVWS channels are summarized in Figure 4.5. The blue bars represent the power-control model results, and the red bars represent the keep-away region model results. It can be seen that among all 12 locations there are 7 locations where the proposed power-control model can provide more available TVWS channels than the keep-away region model. This demonstrates that the proposed model is more efficient in obtaining TVWS information than the keep-away region model.

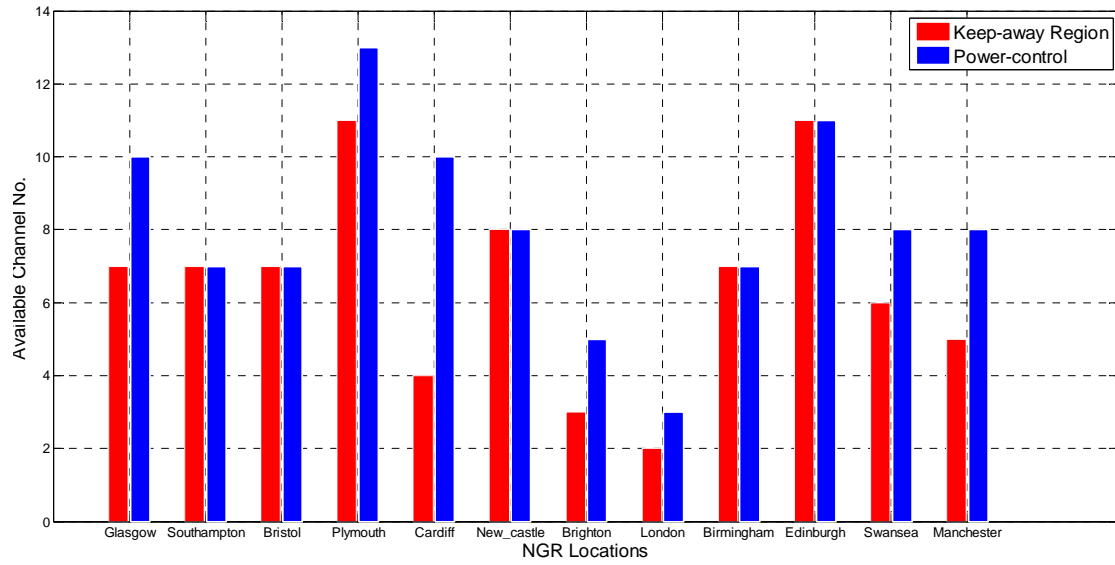


Figure 4.5 Available TVWS information of 12 locations in UK

2) Comparing with the Existing DTV Transmitter Information

The results of the proposed power-control Geo-location database model are also verified with the results of DTV transmitter database from Digital UK, which is a not-for-profit organisation formed by the broadcasters to assist consumers in the conversion to digital TV [98].

By entering a location in Newcastle (National Grid Reference: NZ255645), Digital UK website returns the available DTV transmitters and operational channels. The results taken from the website are shown in Table 4.5 [99]. The results of the proposed Geo-location database model by entering the same location are shown in Table 4.6.

Table 4.5 Available DTV transmitters and operational channels in Newcastle (NZ255645)

Transmitter	BBC A	D3 &4	BBC B HD	SDN	Arqiva A	Arqiva B
	Channel	Channel	Channel	Channel	Channel	Channel
Pontop Pike	58	54	49	50	59	55
Fenham	27	24	21	25	22	28

Table 4.6 Available TVWS information in Newcastle by power-control model

Newcastle (NZ255645)								
Channel No.	30	48	51	52	53	56	57	60
Max. EIRP (watts)	4	4	4	4	4	4	4	4

For comparison purposes, firstly it should be made clear that results in Table 4.5 are regarded as the indication of which transmitters are operating in Newcastle. In other words, the operational TV channels shown in Table 4.5 are currently used by digital TV transmitters in that area, and should not be used by secondary users as TVWS channels. The results shown in Table 4.6 are the available TVWS channels, which could be used by CR stations. By comparing the results from Table 4.5 and Table 4.6, it can be found that the available TVWS channels in Table 4.6 are not shown in Table 4.5, which proves that the obtained TVWS information from the proposed Geo-location database is correct and does not cause harmful interference to existing DTV service.

4.4 The Proposed Resource Allocation Scheme

4.4.1 Grid-based Resource Allocation

A grid-based resource allocation scheme is proposed to use TVWS in the simplified Femtocell networks. This resource allocation scheme utilizes the power-control Geo-location database model proposed in section 4.3 as the mean to obtain locally available TVWS information.

The terminologies used in the proposed resource allocation scheme are explained as follows:

- Grid size

This is the basic location unit used in the proposed scheme. Each grid is associated with a list of available TVWS channels that can be used within that grid.

- List of available channels

These are the available TVWS channels that are obtained from the Geo-location database for a given location.

- Associated allowed transmit power level

This is the maximum transmit power for each channel assignment. For example, higher powers could be allowed in areas where TV channels are not used by primary users for a distance.

The procedure of the proposed grid-based resource allocation scheme is described as follows:

First, the Macrocell coverage is divided into grid areas. As recommended in the Ofcom report on using Geo-location to enable license-exempt access to TVWS [100], the grid size is chosen to be 100m×100m, as shown in Figure 4.7.

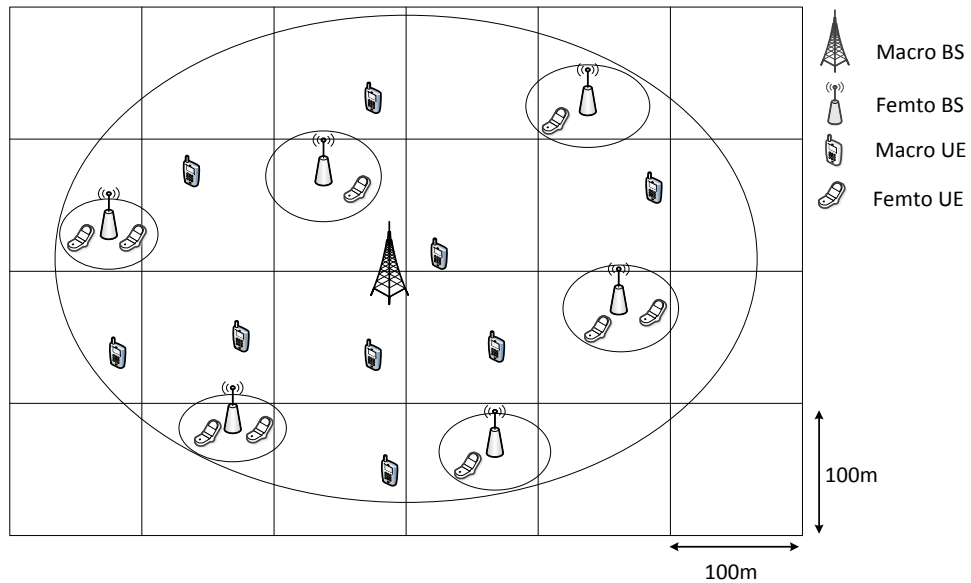


Figure 4.6 Illustration of dividing the cell area into grids

The central controller in a Macro BS is equipped with the proposed power-control Geo-location database model, so that the Macro BS can obtain the available TVWS channel information for given locations. Based on the knowledge of each Femto BS's location, each Femto BS is categorized to a specific grid, and assigned with associated available TVWS channel list in that grid.

Moreover, in order to ensure the protection of primary service, i.e. TV Broadcasting and event-based wireless phone usage, the Geo-location database model can be updated regularly according to the TVWS usage information from local authority. For example, if a registered primary user utilizes some TVWS channels by using wireless phone in a location, with this information, the database should be updated accordingly, making these channels in this location not available for Femtocells to ensure the protection to primary services.

4.4.2 Interference Avoidance Method

1) Possible Interference Cases

- Femtocell - Macrocell

In the proposed scheme, Femtocells and Macrocell are using separate frequency bands: Femtocells use TVWS spectrum band, while Macrocell uses mobile communication spectrum band, so there is no interference between Femtocell and Macrocell.

- Femtocell - Femtocell

There might be possible Femtocell to Femtocell interference, when Femtocells are close to each other, and assigned the same TVWS channels for operations.

2) Interference Avoidance Method

In order to avoid the possible co-channel interference between Femtocells, in the proposed resource allocation scheme, the interference avoidance method is implemented as follows:

First, for each Femto BS, the central controller pre-allocates the first TVWS channel in Femto BS's available TVWS channel list to the Femto BS.

Second, each Femto BS discovers its surrounding Femto BSs, which are within its interference range I_r , and sends this information to the central controller.

Third, the central controller checks the target Femto BS's surrounding Femto BSs' pre-allocated TVWS channels with the target Femto BS's current one.

If there are same channels, delete all the TVWS channels used by surrounding Femto BSs from the target Femto BS's available TVWS channel list, and then re-allocate a new TVWS channel from the list to the target Femto BS, so that to avoid possible interference.

Fourth, the available TVWS channel list of Femto BS is also updated if there are other primary users emerged nearby. If Femto BS uses the same channel as primary users, it has to be changed to another available TVWS channel.

4.4.3 The Overall System Description

The overall system structure for the simplified Femtocell network is illustrated in Figure 4.8. Layers are numbered from bottom to top (Layer 1 to 3):

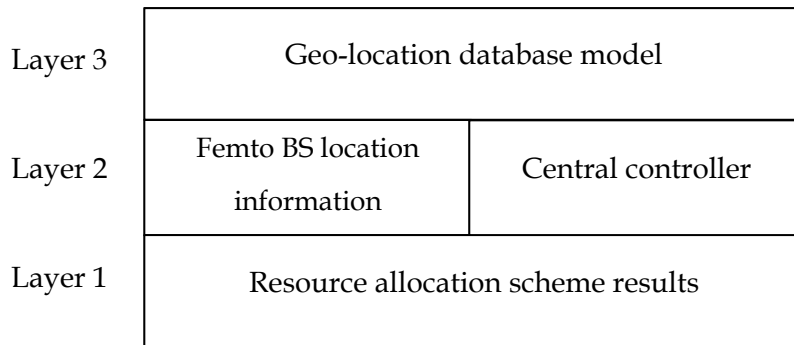


Figure 4.7 The overall system structure

Layer3: Given a specific location, the Geo-location database model can return available TVWS channel list for that location and the associated maximum allowable transmit power.

Layer2: Based the Geo-location database information and Femto BS location information, the central controller performs the proposed resource allocation scheme.

Layer1: Resource allocation scheme results are obtained, and are delivered to each Femto BS.

4.5 Simulation Results and Analysis

1) Network Layout

Four different network layouts settings are simulated. Table 4.7 illustrates the network layouts settings with different number of Macro and Femto UEs. The network layout of setting 1 is shown in Figure 4.9 as an example, in the diagram the big black triangle represents the Macro BS, the small black triangle represents the Femto BS, and red points are Macro UEs served by Macro BS, while green ones are Femto UEs served by Femto BS.

Table 4.7 Four different network layout settings

	Setting 1	Setting 2	Setting 3	Setting 4
No. of Macro UEs	80	60	40	100
No. of Femto UEs	20	40	60	0
No. of Femto UEs in each Femtocell	2	2	2	0

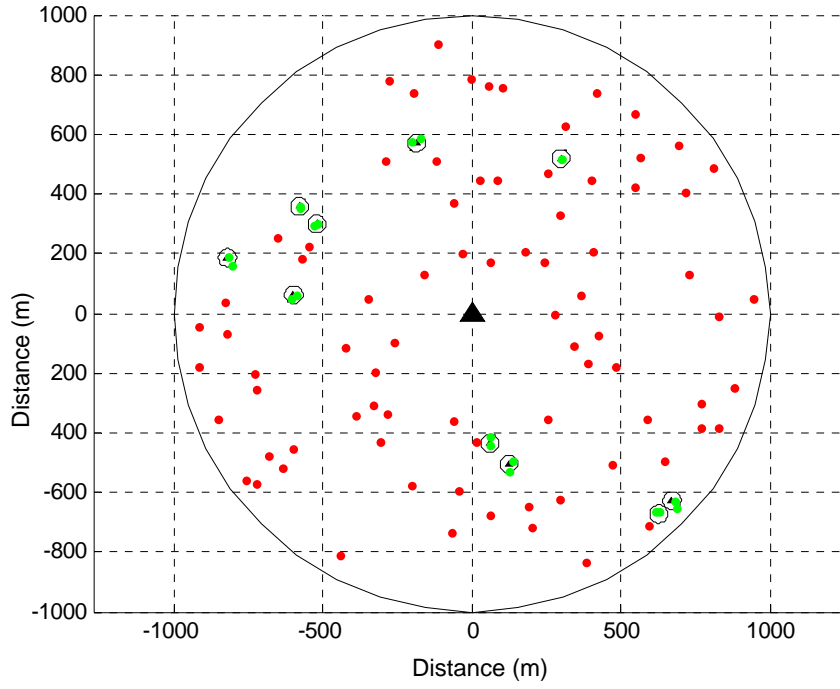


Figure 4.8 Network layout illustration of setting 1

2) Simulation Results and Analysis

The system performance of using TVWS in a simplified Femtocell network based on the Geo-location database model is studied in simulations. The simulator used is the simplified Femtocell networks simulator introduced in section 3.2. Simulation parameters adopted are introduced in section 3.2.4. The performance variation of the proposed scheme with different number of Femtocells deployed is evaluated. In Figure 4.10, the vertical axis indicates the total system throughput which is calculated by using the Shannon equation, and horizontal axis is the number of simulation round. The total number of users is 100. The green line is when there are 30 Femtocells in the Macrocell (i.e. 60 Femto UEs and 40 Macro UEs), while yellow line is when 20 Femtocells, and red line, 10 Femtocells. The blue line is the total system throughput when there is no Femtocell and all UEs are served by the Macro BS.

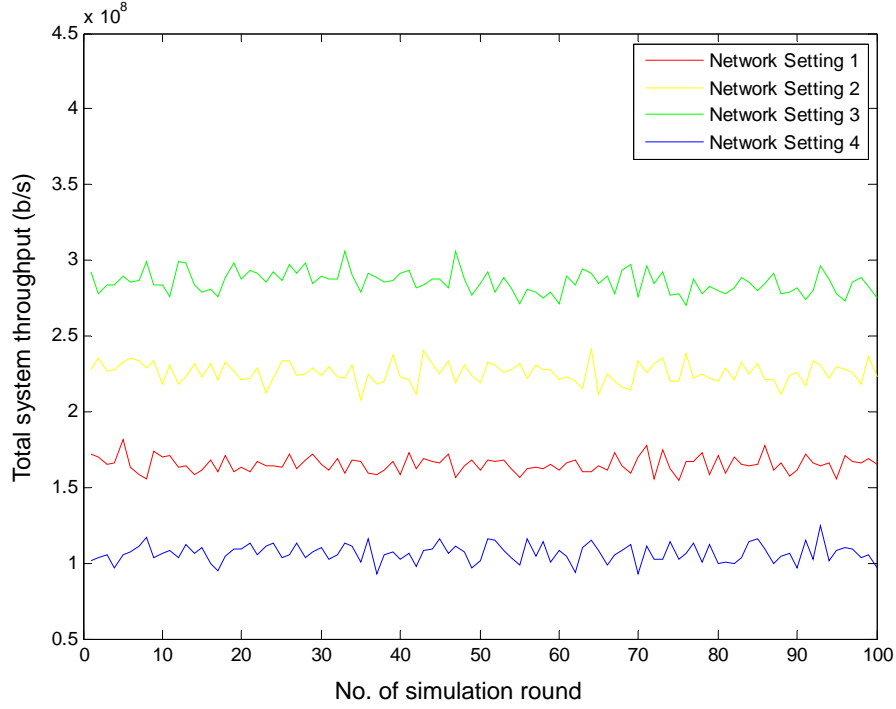


Figure 4.9 System throughputs with different number of Femtocells

As it can be seen from Figure 4.10, when Femtocells using TVWS are deployed (10, 20 and 30 Femtocells), the corresponding system throughput outperforms the traditional Macrocell for more than 50%. This is because that the deployment of Femtocells makes the transmitter and receiver closer, thus user has better SNR, and therefore system throughput is increased. Moreover, the system throughput when 30 Femtocells are deployed is larger than that of 20 and 10 Femtocells. This indicates that when the total user number is fixed, the more users being served by Femtocell, the higher the total system throughput can be obtained.

In addition to the system throughput, the stability of the simulator is also studied in order to demonstrate the reliability of the simulation results. Figure 4.11 shows that how the system capacity varies when there are 20 Femtocells with 40 Femto UEs, and 60 Macro UEs. Different rounds, e.g. 50, 100 and 150, are run for 10 times for each case. The vertical line indicates the total system throughput per round, and horizontal line indicates the n_{th} time of simulation. The red line represents 50 rounds, blue line represents 100 rounds, and green line represents 150 rounds. As shown in Figure 4.11, the three lines are very similar, proving that the simulation result is stable.

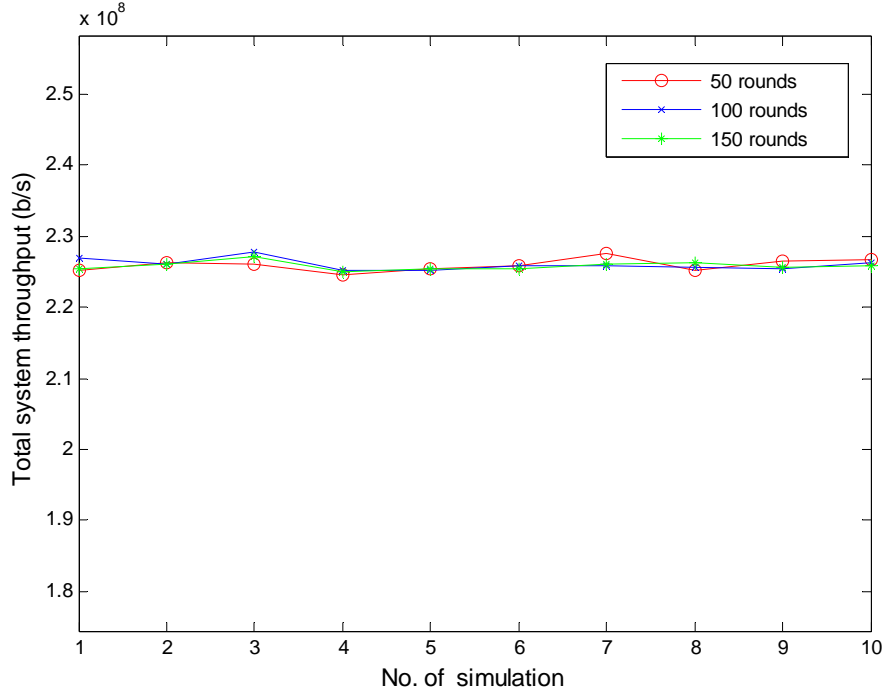


Figure 4.10 Simulator stability of different number of simulation rounds

4.6 Summary

In this chapter, firstly a power-control Geo-location database model for obtaining locally available TVWS was proposed. The proposed database model adopted a power control strategy, thus it can dynamically determine the possible maximum transmit power for CR stations. The database model results were compared and verified by a keep-away region model and an existing DTV transmitter database from Digital UK. From the obtained results it can be concluded that the proposed database model was more efficient in obtaining TVWS information than the keep-away region model. When use the proposed database model, more available TVWS channels can be obtained with various maximum allowable transmit power.

Furthermore, a grid-based plus interference avoidance resource allocation scheme was proposed to utilize the TVWS for Femtocell networks to improve the system performance. In the proposed scheme, Femto BSs were assigned with associated available TVWS channel list based on their grid locations. An interference avoidance method was introduced to reduce the possible co-channel interference between

Femtocells. Simulation results have shown that there was more than 50% improvement in system throughput in comparison with traditional network. From the obtained results it can be concluded that deploying Femtocells that are using TVWS in Macrocell network is an effective way to increase the system throughput, and the incurred throughput gain is getting higher as the number of deployed Femtocells increases.

In the next chapter, the power-control Geo-location database for obtaining locally available TVWS is applied to the OFDMA-based Femtocell networks with suburban deployment for cross-tier interference mitigation.

Chapter 5 Cross-tier Interference Mitigation

in Suburban Femtocell Deployment

5.1 Introduction

Following the work in Chapter 4, the TVWS is applied to suburban Femtocell deployment in this chapter. A novel system architecture of using TVWS is proposed to mitigate the cross-tier interference in suburban Femtocell deployment. The proposed system architecture includes: (i) the Geo-location database model designed in section 4.3 to obtain locally available TVWS information, and (ii) a novel resource allocation scheme using the locally available TVWS to mitigate the downlink cross-tier interference between Macro UEs and nearby Femtocells. Simulations in suburban and cell edge areas are conducted to compare the performance of the proposed scheme with other existing schemes.

5.2 Suburban Femtocell Deployment

In suburban Femtocell deployment, Femtocells are often installed in separate houses, as shown in Figure 5.1. In this case, since Femtocells are sparsely located in the Macrocell coverage area, there is little co-tier interference among them. The cross-tier interference between Femtocell and Macro UEs is the main interference.

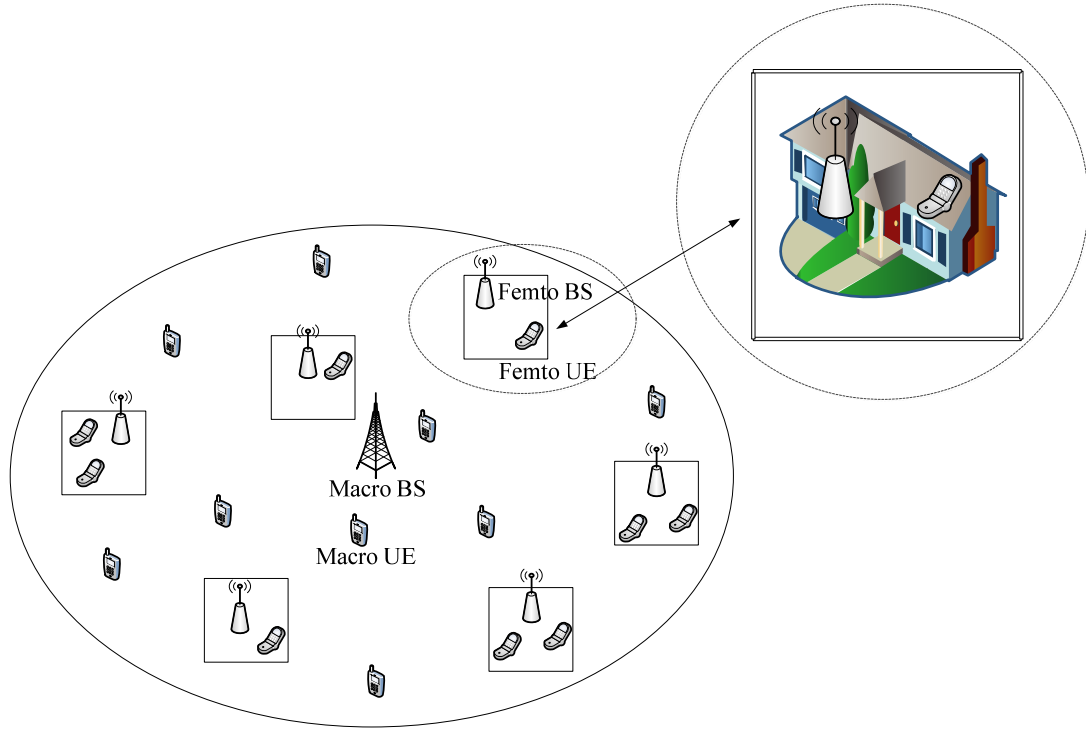


Figure 5.1 Illustration of suburban Femtocell deployment

The scenario investigated in this chapter is a two-tier OFDMA-based network that consists of an isolated Macrocell with suburban Femtocell deployment. This work is focused on the downlink transmission. Femtocells are assumed to operate in the “closed access” mode, which restricts the use of Femtocells to users explicitly approved by owners [101]. In other words, Femtocells only serve Femto UEs, and are not open to Macro UEs. In suburban Femtocell deployment, conventionally Femto BSs access the same frequency spectrum as the Macro BS, and therefore Femto BSs may produce cross-tier interference to nearby Macro UEs that are using the same sub-channels.

The downlink cross-tier interference scenario in suburban Femtocell deployment is illustrated in Figure 5.2. There are four types of network entities in this network scenario, namely Macro BS, Macro UE (MUE), Femto BS and Femto UE (FUE). When a MUE is very close to a Femto BS or even within the Femto BS’s coverage, it experiences high interference from nearby Femtocell operating in the co-channel. As shown in Figure 5.2, a MUE is far away from the Macro BS and is located around a Femto BS’s coverage edge. If the Femto BS uses the same sub-channel as the MUE does, then this MUE experiences severe cross-tier interference from the Femto BS and has poor SINR.

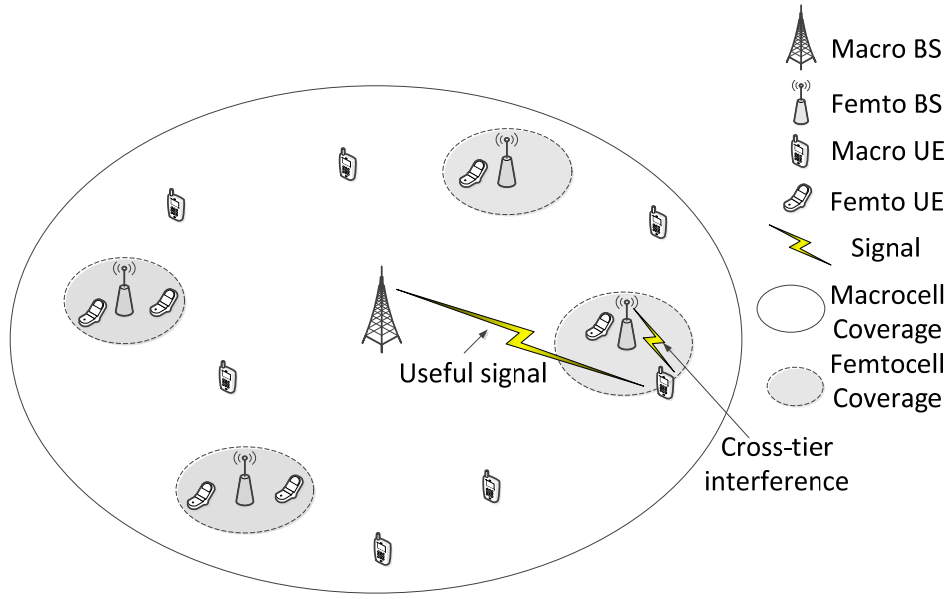


Figure 5.2 Illustration of cross-tier interference between Macro UE and Femto BS in suburban Femtocell deployment scenario

Current research on reducing cross-tier interference in Femtocell networks is reviewed in section 2.2.4. These approaches are generally based on the licensed cellular frequency band, and have limited performance improvement at the expense of complexity. TVWS has been applied to a simplified Femtocell network in Chapter 4. In this chapter, a novel system architecture of using TVWS in OFDMA Femtocell networks with suburban deployment is proposed. The proposed system architecture includes: 1) a Geo-location database method introduced in section 4.3 to obtain the locally available TVWS information; and 2) a resource allocation scheme to use the locally available TVWS to mitigate the downlink cross-tier interference in the suburban Femtocell deployment.

5.3 The Proposed System Architecture

5.3.1 System Architecture

The proposed system architecture of using TVWS to mitigate cross-tier interference in suburban Femtocell deployment is shown in Figure 5.3. The Geo-location database used in the proposed system has been introduced in section 4.3. System components include:

- **Central Controller** is located in the Macro BS and conducts the resource allocation.
- **Geo-location Database** is co-located with the central controller, and stores TVWS information.
- **Femto BSs** are located randomly in the Macrocell area.
- **Users** include Macro UEs and Femto UEs.

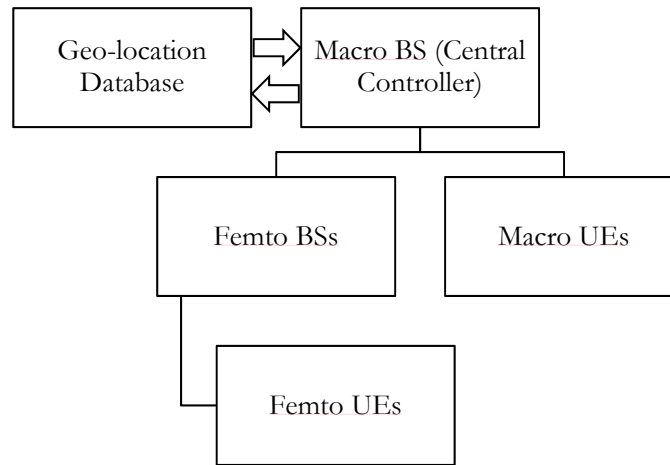


Figure 5.3 The proposed system architecture

5.3.2 The Resource Allocation Scheme Using TVWS

Considering the downlink interference scenario in OFDMA Femtocell networks, a Macro UE n served by Macro base station is located closely to or within the coverage of Femto BS i . In this case, the most straightforward and effective way to mitigate the Femto BS to Macro UE cross-tier interference is to assign different spectrum portions for Femtocell and Macrocell respectively. For instance, Femto BS i is denied access to sub-channels allocated to Macro UE n in order to avoid the potential co-channel interference. The interference from nearby Femto BS i to Macro UE n is mitigated, and the SINR of Macro UE n will be improved. The traditional approach of doing this is using resource partitioning which is to allocate separate mobile spectrum bands for Macrocells and Femtocells. However, this approach would not be spectrum efficient, and it mitigates the interference at the expense of low utilization

of licensed spectrum since Macro UEs or Femto UEs only use part of the whole spectrum.

In the proposed system architecture, the Macro BS can obtain the available TVWS information in its coverage area from the co-located Geo-location database, and schedule the resource allocation. A novel resource allocation scheme using the obtained TVWS is proposed to reduce the downlink cross-tier interference between Femtocells and nearby MUEs. The basic idea of the proposed scheme is to assess which of the Femtocells are causing interference to one or more Macro UEs at a given point, and then those interfering Femtocells, e.g. red Femto BSs shown in Figure 5.4, are temporarily allocated with the obtained TVWS spectrum resource to avoid their potential interference on nearby Macro UEs. The proposed scheme is aiming to reduce the cross-tier interference by utilizing locally available TVWS spectrum resource, rather than partitioning the licensed mobile spectrum band, so that spectrum utilization is improved.

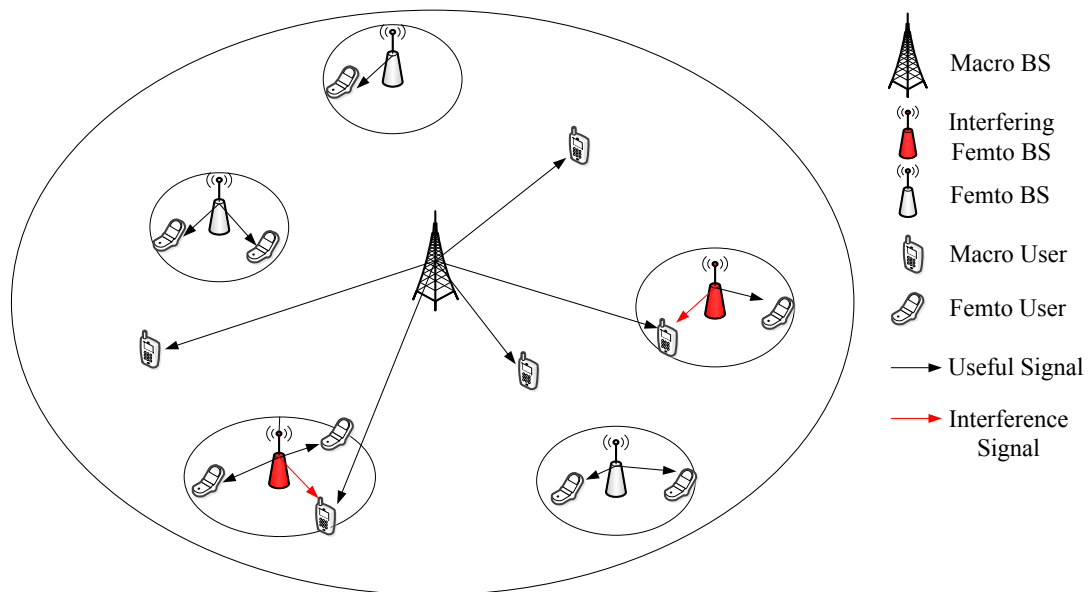


Figure 5.4 Illustration of interfering Femtocells

The proposed scheme consists of two steps, which are the Femtocell classification and the resource allocation:

Step 1. Femtocell Classification

The classification step relies on the measurement reports from Macro UEs (MUEs). It is assumed that MUEs can arbitrarily detect the Reference Signal Received Power (RSRP) from Macro BS (as the desired signal) and each Femto BS (as interference) in the downlink. Depending on the received RSRP signal power from Macro BS and Femto BSs, a MUE can calculate the receiving SINRs.

If the receiving SINR at a MUE is lower than the pre-defined threshold ν_{th} (the predefined SINR threshold used in this work is based on the one introduced in [102]), the related Femtocells are categorized as *interfering*, otherwise *non-interfering*. The Macro UE then adds the interfering Femtocells IDs into its interference set Set_i and send measurement reports containing Femtocell interference information to Macro BS for further processing. All the information is supposed to be transferred over the air interface.

Step 2. Resource Allocation

After Femtocell classification, the central controller in Macro BS performs resource allocation according to the MUE measurements reports and the available TVWS information from Geo-location database. In this step, TVWS availability information is obtained by Macro BS from the co-located Geo-location TVWS database model introduced in section 4.3. Macro BS allocates the available TVWS in terms of sub-channels to interfering Femtocells, and allocates mobile spectrum sub-channels to non-interfering Femtocells and MUEs.

The procedure of the proposed resource allocation scheme is summarized in Table 5.1. In the description of the scheme, m is the index of a MUE in the Macrocell. i is the index of a Femto BS in the Macrocell. $SINR_{m,i}$ denotes the SINR of MUE m when signal P_m from Macro BS is regarded as the desired signal and signal I_i from Femto BS i as the interference.

Table 5.1 Procedure of the proposed resource allocation scheme

START:

Step1: Femtocell Classification

1. Every MUE m estimates the Reference Signal Received Power (RSRP) from Macro BS and each Femto BS in the downlink.
2. Compute the $SINR_{m,i}$ of MUE m for every Femto BS i , by using the received RSRP signal P_m from Macro BS as desired signal and RSRP signal I_i from Femto BS i as interference. σ^2 represents the thermal noise.

$$SINR_{m,i} = \frac{P_m}{I_i + \sigma^2}$$

3. Compare the $SINR_{m,i}$ at MUE m with the threshold v_{th}
4. Femtocell i is marked by MUE m as non-interfering Femtocell if the $SINR_{m,i}$ is larger than the threshold, otherwise, it is marked as an interfering Femtocell to that MUE m .
5. Each MUE m sends its Femtocell interference information to Macro BS.

Step2: Resource Allocation

6. The central controller in Macro BS will sort the interfering and non-interfering Femtocells results from all MUEs reports. Femtocells which are marked as interfering by one or more MUEs will be regarded as interfering Femtocells.
7. Based on the obtained TVWS information from co-located Geo-location database. The central controller will allocate TVWS sub-channels to interfering Femtocells in a round-robin manner, and allocate mobile spectrum sub-channels to non-interfering Femtocells and MUEs in a round-robin manner.

END

For the proposed scheme described in Table 5.1, the system operating sequence chart is illustrated in Figure 5.5.

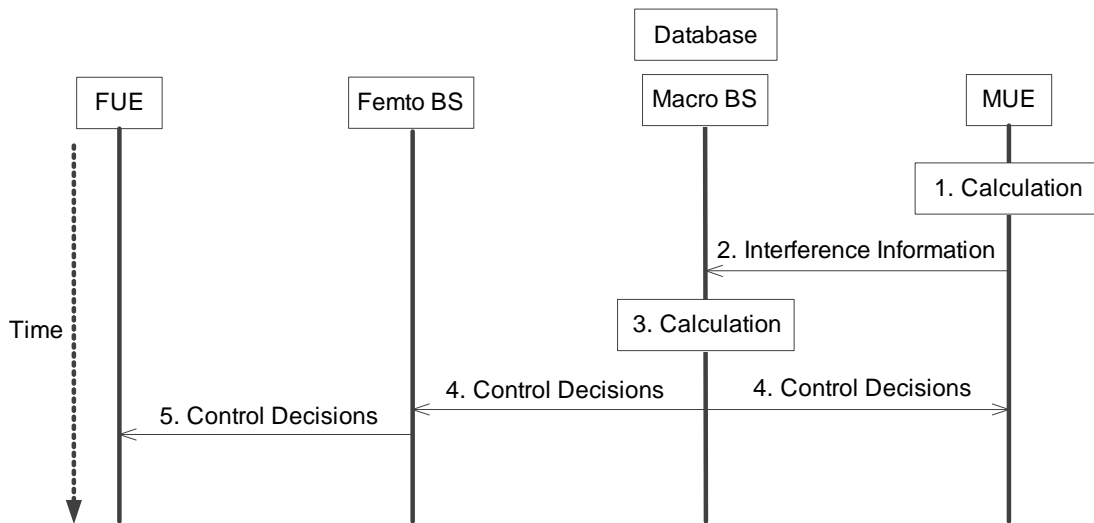


Figure 5.5 System operating sequence chart

5.4 Simulation Results and Analysis

The proposed system architecture is evaluated in two simulated scenarios: suburban area and cell edge area scenarios.

5.4.1 Suburban Area Scenario

5.4.1.1 Scenario Description

The network layout of the simulated suburban area scenario is illustrated in Figure 5.6. It is assumed that the Macrocell is located around the campus of Queen Mary, University of London (QMUL). The simulator used is the two-tier OFDMA Femtocell networks simulator with suburban deployment introduced in section 3.3. It is built according to the suburban Femtocell modelling in 3GPP specifications on HeNB simulation [91]. The simulation parameters adopted are introduced in section 3.3.4. Femto BSs are randomly dropped within the houses. Macro/Femto UEs are randomly dropped within the outdoors/indoors Macrocell coverage area, subject to a minimum separation to Macro BS/Femto BSs. A Macro UE may be within a house. The black triangle represents the Macro BS, green points are Macro UEs, and blue

squares are houses with surrounding space. The more detailed view of the houses with surrounding space is shown in Figure 5.7. Small black triangles within each house are Femto BSs, and red points inside the houses are Femto UEs.

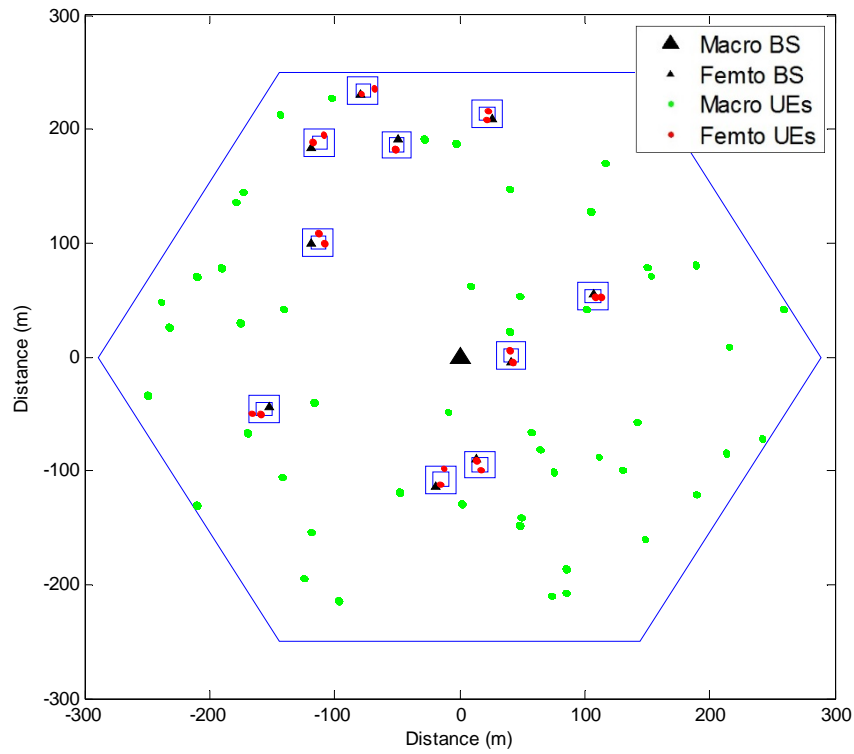


Figure 5.6 Illustration of the simulated suburban area scenario

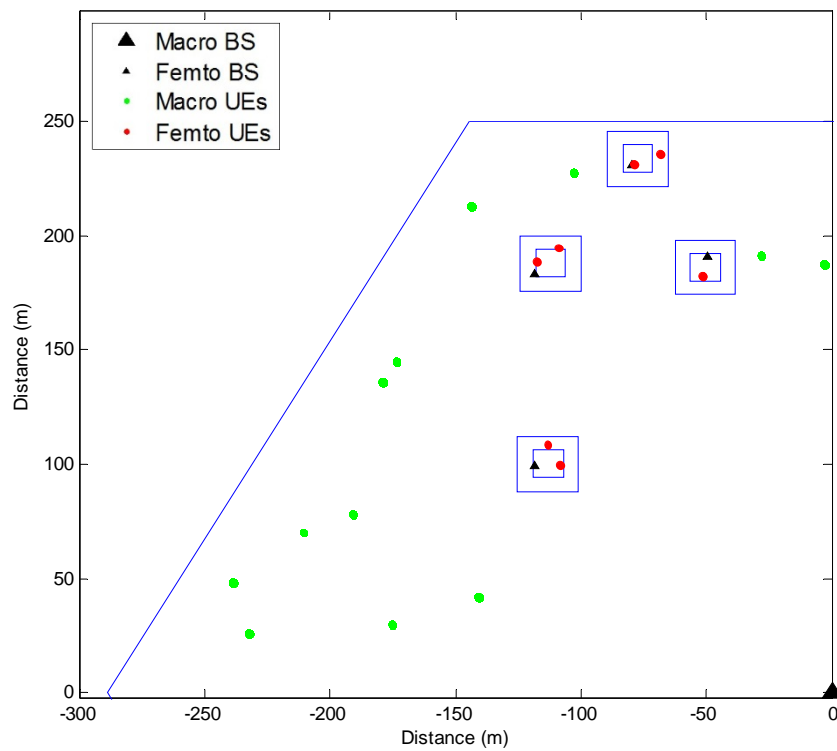


Figure 5.7 Detailed view of houses with Femtocells

5.4.1.2 Results and Analysis

The simulations run for a full-buffer traffic model, which means all users in the system are active simultaneously. Each run of the simulation is iterated over 1000 snapshots to obtain statistically accurate results. Moreover, users in the system are assumed to be static for the duration of the snapshot. Perfect synchronization in both time and frequency is assumed, so that interference between adjacent sub-channels can be neglected.

The simulated location is at QMUL with the post code E1 4NS (National Grid Reference: TQ360823). Table 5.2 shows the available TVWS information results returned from the Geo-location database. As it can be seen from Table 5.2, there are 4 TVWS channels (channel 29, 50, 56, 58) available in this location. The maximum allowable transmit power of channel 29, 50, 58 is 4W, while for channel 56 it is about 0.315W, which is still sufficient for Femtocell, whose maximum transmit power is just about 0.1W [91].

Table 5.2 Available TVWS information results from Geo-location database (simulated location at Queen Mary, University of London)

NGR Number of location: TQ360823				
Channel No.	29	50	56	58
Maximum Allowable EIRP(watts)	4.000	4.000	0.315	4.000

1) Interference Mitigation Performance Compared with Traditional Scheme

In this case, there are 10 Femtocells randomly located in the Macrocell, 2 Femto UEs in each Femtocell, and 50 Macro UEs randomly located in the Macrocell area, and the Macrocell radius is 288m (i.e. inter-site distance 500m).

This case focuses on mitigating cross-tier interference suffered by Macro UEs from nearby Femto BSs. In order to compare with the proposed resource allocation scheme, a traditional resource allocation scheme is implemented as a benchmark, in which Femto BSs and Macro BS operate on the same spectrum band. The whole bandwidth is shared among Macro and Femto UEs. Therefore, the downlink interference

experienced by Macro UEs should be strong in this scheme. In the simulations of the traditional scheme, the same parameters as those used in the proposed scheme are employed.

The comparison of the system interference between the proposed scheme and traditional scheme is shown in Figure 5.8 in terms of the cumulative distribution functions (CDF) of the downlink interference suffered by Macro UEs. The SINR threshold is set to be -8dB. The red line indicates the traditional All-shared resource allocation scheme, while the blue line indicates the proposed scheme. As it can be seen from Figure 5.8, the proposed scheme outperforms the traditional one greatly, and reduces the interference by about 4.5dB at the 70th percentile. This is because the potential interfering Femtocells in the proposed scheme are identified and allocated with TVWS sub-channels from Macro BS rather than with sub-channels in the same frequency band as Macro UEs. Hence, the cross-tier interference from Femto BSs to Macro UEs is significantly reduced.

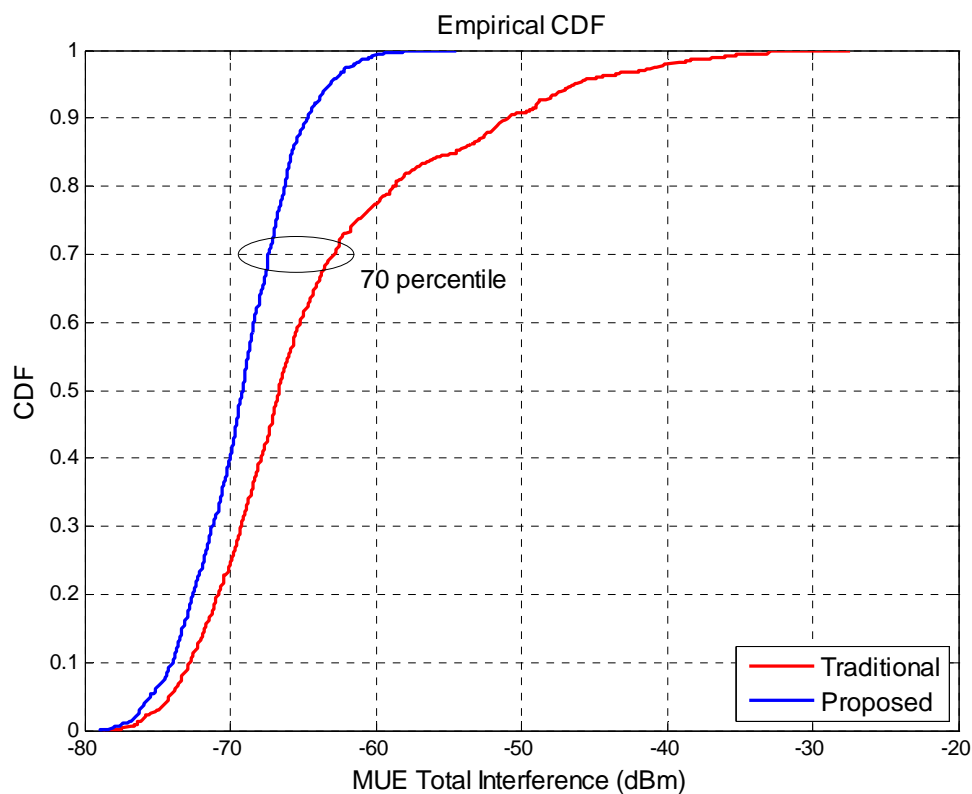


Figure 5.8 Interference comparison between traditional and the proposed schemes

2) Interference Mitigation Performance Compared with Dynamic Resource Partitioning Scheme

The authors in [103] proposed a dynamic resource partitioning (DRP) scheme to mitigate the downlink Femtocell to Macrocell interference. The basic idea of this DRP scheme is to deny Femto BSs' access to sub-channels which have been allocated to nearby Macro UEs in order to reduce the interference originated from the interfering Femto BSs. The DRP scheme with the same parameters as those used in the proposed scheme is simulated in this research and compared with the proposed scheme.

In Figure 5.9, the red line indicates the traditional All-shared resource allocation scheme, while the blue line indicates the proposed resource allocation scheme using TVWS, and the green line indicates the DRP scheme. As it can be seen from Figure 5.9, the proposed scheme reduces the interference that Macro UEs experience by about 3.5dB in comparison with the DRP scheme at the 70th percentile. The performance of DRP scheme lies between the proposed scheme and traditional scheme as predicted.

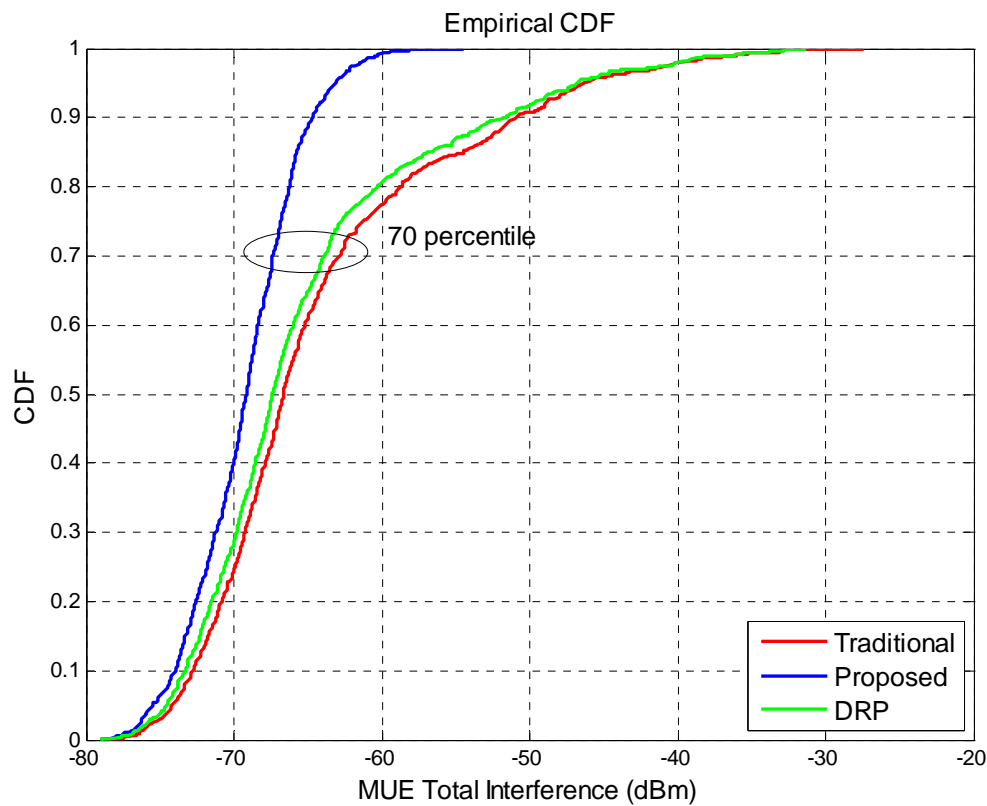


Figure 5.9 Interference comparison among traditional, DRP and the proposed schemes

3) Impacts on Performance of Different SINR Thresholds

Furthermore, the pre-defined interference threshold in the proposed scheme is investigated to understand impacts on the system performance when different SINR thresholds are applied. Figure 5.10 shows the interference mitigation performance comparison of different SINR thresholds, e.g. -6, -8 and -10dB. Other parameter settings are the same as those in case 1 (Interference Mitigation Performance Compared with Traditional Scheme). As shown in Figure 5.10, when the SINR threshold equals to -6dB which is indicated by the red curve, the interference mitigation performance is slightly better than the cases when the threshold equals to -8dB or -10dB. This is because that higher threshold leads to more Femtocells to be categorized as interfering Femtocells and more TVWS sub-channels are allocated to Femto BSs to avoid potential cross-tier interference. However, higher threshold also leads to more Femtocell interference information as overheads sent from Macro UEs to Macro BS, and more TVWS spectrum resource to be required as well. In the proposed scheme, by considering both of the performance and the cost, the SINR threshold is chosen as -8dB, which is also the threshold value adopted in [102].

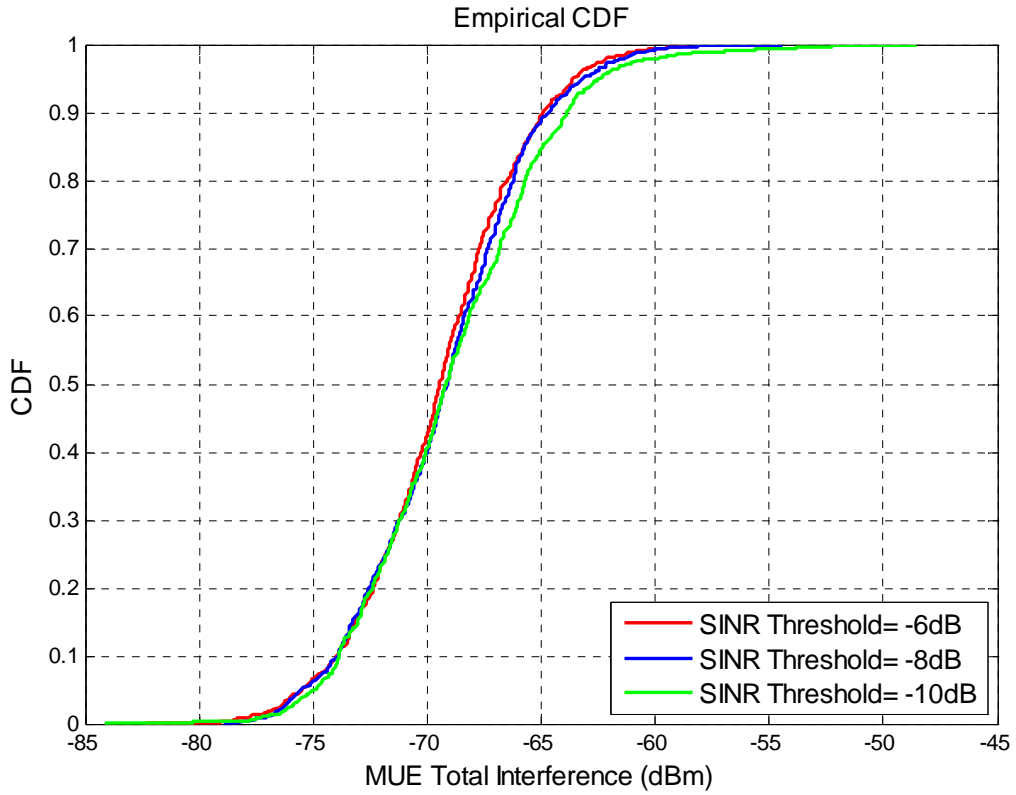


Figure 5.10 Interference comparison of different SINR thresholds

4) Impacts on Performance of Different Number of Femtocells

Variations of the interference mitigation are examined at different number of Femtocells. In this case, the number of Femtocells within the Macrocell is set to be 10, 15, and 20, respectively. There are 2 Femto UEs in each Femtocell. Other parameter settings are the same as those in case 1 (Interference Mitigation Performance Compared with Traditional Scheme).

Figure 5.11 shows the interference mitigation performance variation with different numbers of Femtocells in comparison with the traditional All-shared scheme. It can be observed from the diagram that as the number of Femtocells increases, e.g. from 10, 15 to 20, the downlink interference experienced by Macro UEs also increases, which can be seen in Figure 5.11 that the CDF curve is moving to the right as the Femtocell number increases. When the proposed scheme is applied, as the Femtocell number increases by the step size of 5, the interference increases by about 2dB on average at the 70th percentile, which is smaller than with the traditional scheme (about 4dB).

Therefore, as the number of Femtocells increases, the proposed scheme is around 2dB better than the traditional scheme in limiting the increase of interference incurred. This indicates that when there are more Femtocells deployed, Macro UEs with the proposed scheme experience less cross-tier interference than that of the All-shared scheme.

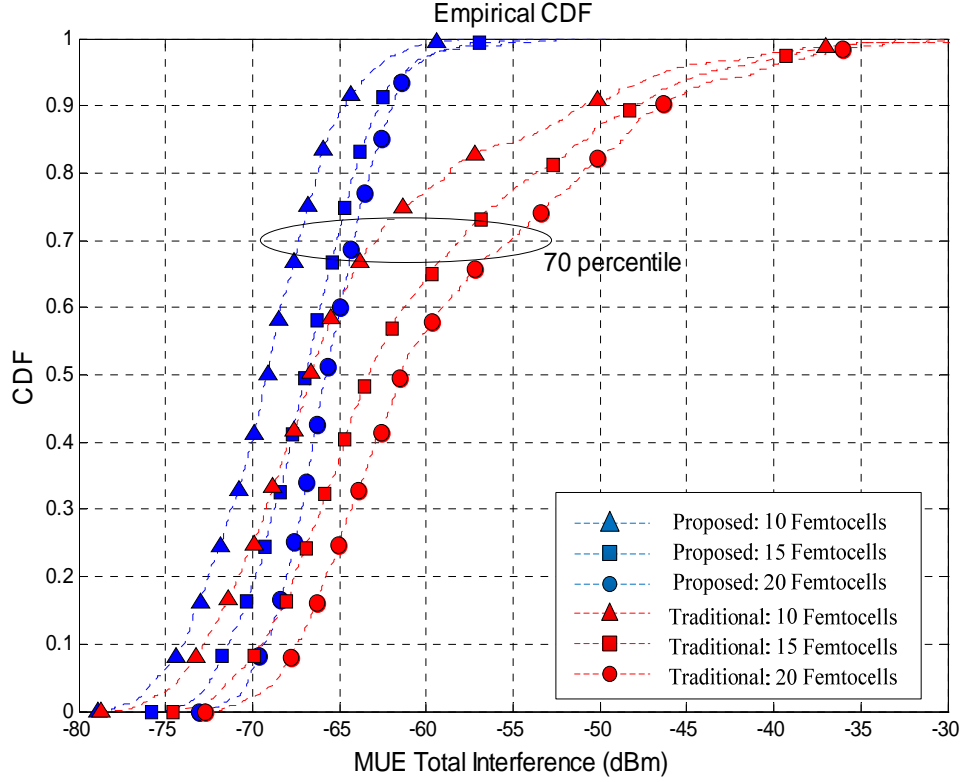


Figure 5.11 Interference comparisons of different number of Femtocells

5) Impacts on Performance of Different Sizes of Macrocell

The impacts of different Macrocell cell sizes on interference mitigation performance of the proposed scheme are also studied. In this case, the Macrocell radius is set to be 144, 288, and 577m, i.e. inter-site distance 250, 500, and 1000m, respectively. There are 50 Macro UEs, 10 Femtocells in the Macrocell area with 2 Femto UEs in each Femtocell. Other parameter settings are the same as those in case 1 (Interference Mitigation Performance Compared with Traditional Scheme).

As shown in Figure 5.12, the interference experienced by Macro UEs becomes smaller in a larger Macrocell. This is due to the larger average distance between Femto BS and Macro UEs. It can be observed that in a Macrocell with a radius of 144 m, the proposed scheme reduces the interference by about 10dB at the 70th percentile in comparison with the traditional scheme. For a Macrocell with a radius of 288m, it reduces the interference by about 4.5dB. For a Macrocell with a radius of 577m, the proposed scheme reduces the interference by about 3.5dB. This indicates that when the Macrocell is smaller, the proposed scheme achieves a larger improvement against the traditional scheme, and the Macro UEs experience much less interference.

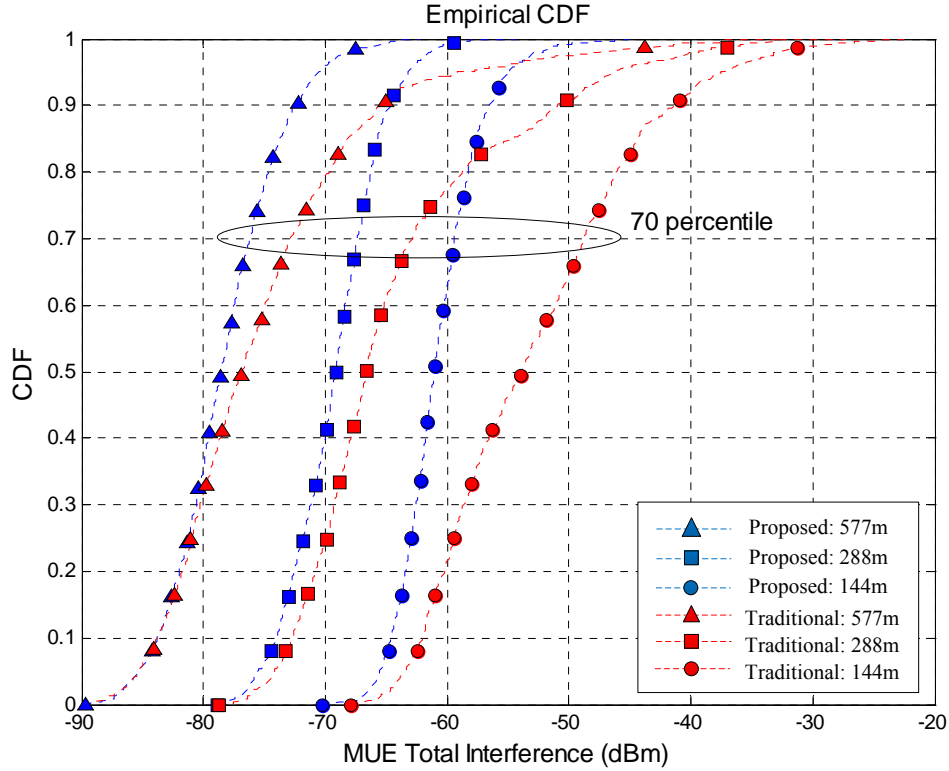


Figure 5.12 Interference comparison of different Macrocell radii

5.4.2 Cell Edge Area Scenario

5.4.2.1 Scenario Description

In traditional Macrocell networks, the Macro UEs in cell edge experience poor signal coverage and low SINR. This is because that they suffer high path loss than cell interior users and the received signal strength transmitted from the Macro BS is very weak. The indoor Macro UEs in cell edge area suffer even heavier. Femtocells are likely to be installed in houses in the cell edge area, in order to improve the signal reception for indoor users. In this case, the cross-tier interference from nearby Femtocells makes the SINR of outdoor Macro UEs even worse.

As illustrated in Figure 5.13, a Macro UE is at the Macrocell edge and there is a Femtocell operating in close proximity of that Macro UE. In this scenario, the signal from the Macro BS to that Macro UE is weak due to the high path loss, while the signal of the Femto BS downlink is strong, and therefore the Macro UE faces strong

cross-tier interference from nearby Femtocell, which results in even lower SINR at the Macro UE.

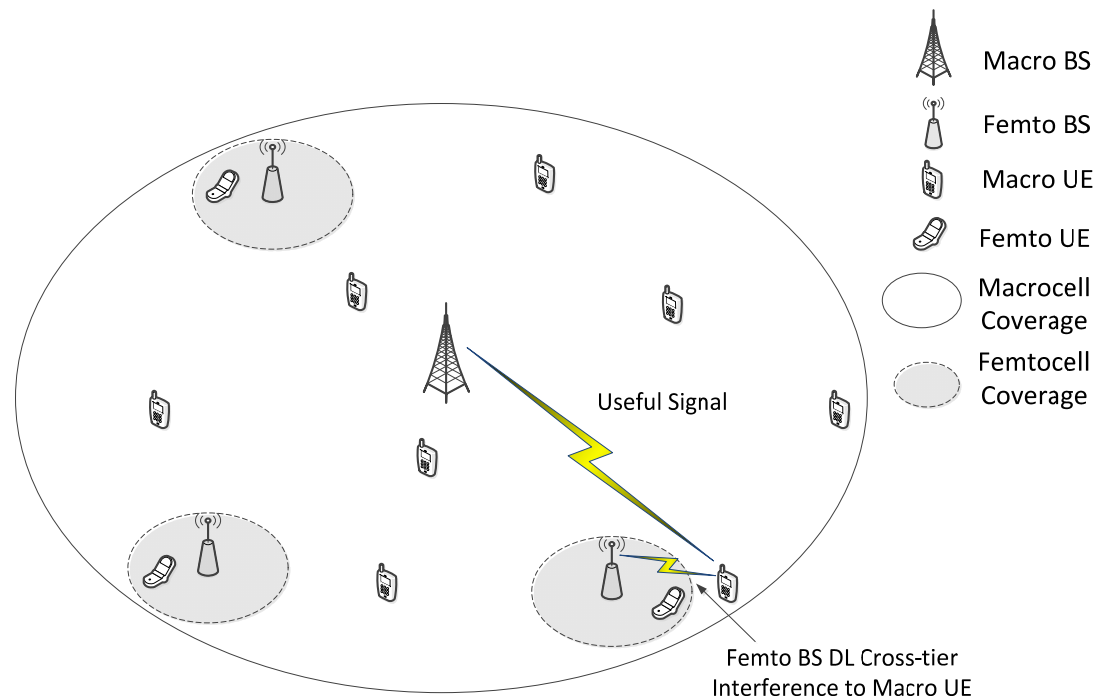


Figure 5.13 Illustration of cross-tier interference suffered by MUE at cell edge

The proposed system architecture introduced in section 5.3 is applied to suburban Femtocell deployment in cell edge area scenario to investigate the performance. The simulator used in this scenario is the two-tier OFDMA Femtocell networks simulator with suburban Femtocell deployment introduced in section 3.3.

In the simulated cell edge area, Femto BSs are randomly dropped within the houses. Macro/Femto UEs are randomly dropped within the outdoors/indoors Macrocell coverage area. The “closed access” mode of Femtocell is assumed. The network layout of the simulated cell edge area scenario is illustrated in Figure 5.14. The black triangle represents the Macro BS, green points are Macro UEs, and blue squares are houses with surrounding space. Small black triangles within each house are Femto BSs, and red points inside the houses are Femto UEs.

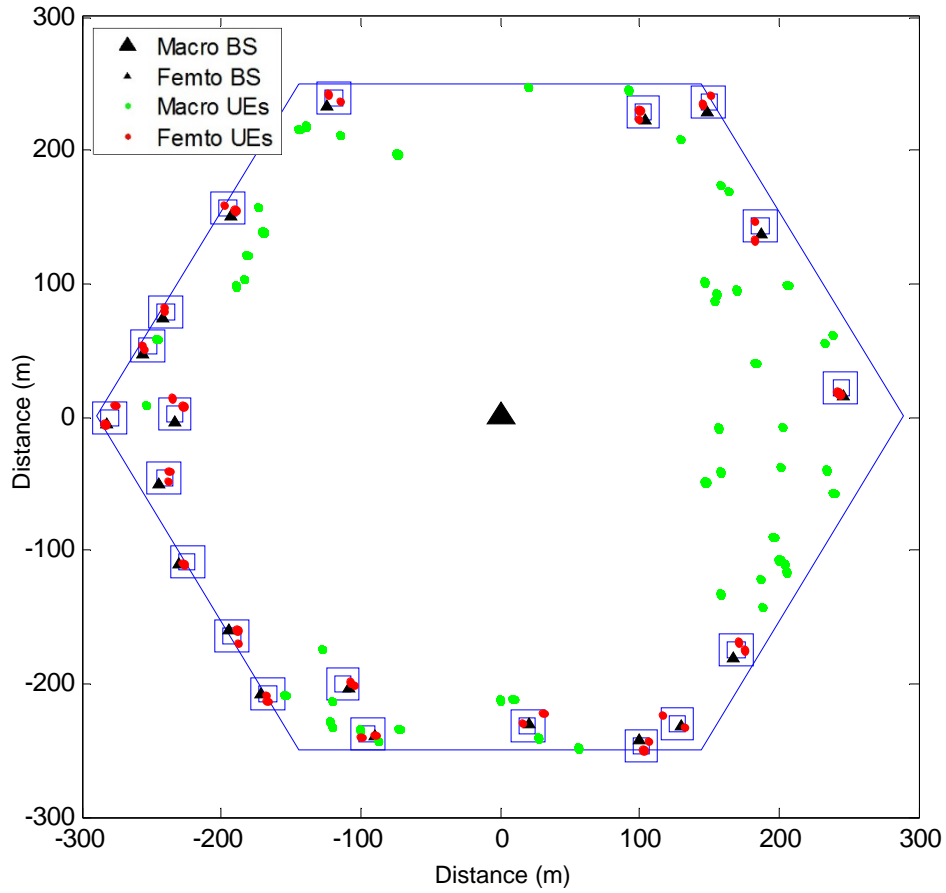


Figure 5.14 Illustration of the simulated cell edge area scenario

5.4.2.2 Results and Analysis

In the simulation, there are 20 Femtocells with 2 Femto UEs in each Femtocell, and 50 Macro UEs randomly distributed in the cell edge area. Other simulation assumptions and parameters are the same as in suburban area scenario discussed in section 5.4.1. The available TVWS channels and associated maximum allowable transmit power information are adopted from Table 5.2 in section 5.4.1.2.

For the purpose of comparison, a traditional All-shared resource allocation scheme is implemented as a benchmark, in which Femto BSs and Macro BS operate on the same spectrum band. So the whole bandwidth is shared among Macro and Femto UEs. The proposed scheme is compared with the traditional scheme, as shown in Figure 5.15, in terms of the cumulative distribution functions (CDF) of average SINR

of Macro UEs. The red line indicates the traditional All-shared resource allocation scheme for comparison, while the blue line indicates the proposed scheme. As it can be seen from the diagram the proposed scheme using TVWS outperforms the traditional one greatly, and it improves the MUE average SINR for about 2dB at the 70th percentile of the CDF diagram. This indicates that in the cell edge area, Macro UEs with the proposed scheme can have better SINR than that of the All-shared scheme.

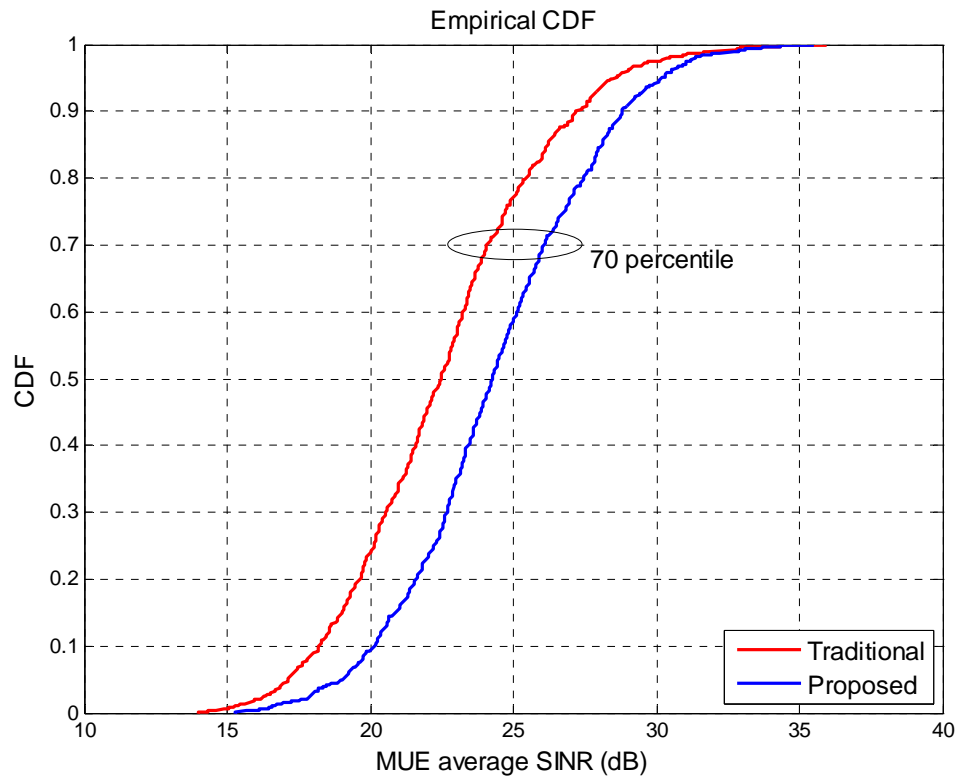


Figure 5.15 MUE average SINR comparison between traditional and the proposed schemes

5.5 Summary

In this chapter, a novel system architecture of using TVWS in suburban Femtocell deployment has been proposed. This architecture included: (i) the Geo-location database model proposed in section 4.3 to obtain locally available TVWS information, and (ii) a novel resource allocation scheme using the locally available TVWS to mitigate the downlink cross-tier interference between Macro UEs and Femtocells. The proposed architecture exemplifies a practical system model that makes use of TVWS in resource allocation in Femtocell networks, by combining the Geo-location database model as the cognitive access method to TVWS and the resource allocation scheme that can allocate TVWS resources. The performance of the proposed system architecture was evaluated in suburban and cell edge scenarios, respectively.

The simulation results have shown that: in the suburban area scenario, the proposed architecture reduced the downlink interference suffered by Macro UEs effectively, by about 4.5dB and 3.5dB at the 70th percentile of the CDF diagram in comparison with the traditional All-shared scheme and the DRP scheme, respectively. An appropriate SINR threshold value of -8dB in the proposed scheme has been identified by considering both of the performance and cost. In the cell edge area scenario, the proposed architecture can improve the MUE average SINR located in cell edge area for about 2dB at the 70th percentile of the CDF diagram in comparison with the traditional All-shared scheme.

Conclusions drawn from the obtained results are worth to be considered in Femtocells deployment: the proposed scheme performed better in the scenarios of more dense Femtocell distribution or smaller Macrocell, and is better in providing higher SINR for MUEs in the cell edge area than the traditional scheme.

In the next chapter, the interference mitigation problem in dense Femtocell deployment will be investigated.

Chapter 6 Co-Tier Interference Mitigation

in Dense Femtocell Deployment

6.1 Introduction

In addition to the scenario of suburban Femtocell deployment as discussed in Chapter 5, Femtocells are also widely installed in rooms of buildings in urban area, which is a very dense deployment. In this scenario, the cross-tier interference between Femtocells and Macro UEs can be mitigated by using TVWS spectrum for Femtocells, with the aid of Geo-location database introduced in Chapter 4. However, the co-tier interference between Femtocells becomes dominant, due to the high density of Femtocells reusing the TVWS spectrum. In dense deployment, the co-tier interference between Femtocells is the main factor limiting the system performance. In this chapter, the co-tier interference in OFDMA Femtocell networks with dense deployment is studied. A power efficient resource allocation scheme is proposed to maximize the throughput of Femtocells while limiting the co-tier interference among Femtocells. The proposed scheme consists of the sub-channel allocation algorithm and the sub-channel power control algorithm. The optimization problem in the proposed power control algorithm is solved by the SQP method.

6.2 Dense Femtocell Deployment

Femtocell offers a promising way of extending Macrocell network coverage to indoor residential environments [104]. In the urban area of a city, Femtocells are often installed in apartments of building blocks to provide better indoor coverage, which often forms a dense Femtocell deployment, as illustrated in Figure 6.1. In this scenario, Femtocells can be deployed in very close proximity in apartments. In OFDMA-based systems, this dense deployment may lead to severe co-tier

interference between Femtocells when they are operating in the same sub-channels, since the wall separation is generally not enough to avoid the interference [105].

In this chapter, a dual strip model is adopted for modelling the dense Femtocell deployment, which is introduced in 3GPP specifications on HeNB simulation [91]. As illustrated in Figure 6.1, in this model each block represents two stripes of apartments, each stripe has 2 by N apartments (N is 10 in the example illustrated in Figure 6.1), and each apartment is of size 10m \times 10m. The street between the two stripes of apartments is also modelled with the width of 10m. Each Femtocell block is of size $10(N+2)\text{m} \times 70\text{m}$ (70m is the width of 4 apartments plus 3 street width). In each Macrocell area, one or several Femtocell blocks are randomly dropped. It is assumed that the Femtocell blocks are not overlapping with each other. Each Femtocell block has L floors, and the floor number is chosen between 1 and 10. If more than one Femtocell blocks are dropped, each Femtocell block can have different number of floors. A typical Femtocell block is illustrated in Figure 6.2.

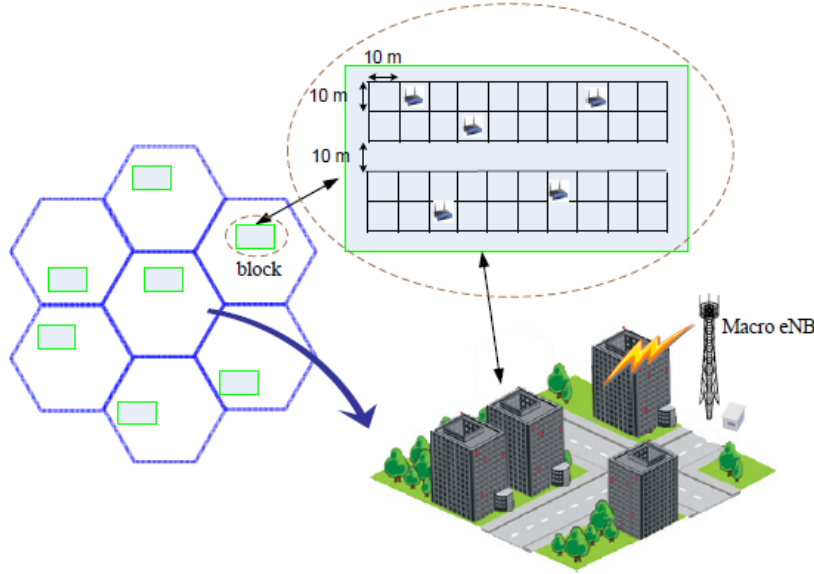


Figure 6.1 Illustration of dense Femtocell deployment [29]

In a realistic case, an apartment may not have a Femto BS, a parameter called “deployment ratio” is introduced to model whether an apartment is deployed with a Femto BS or not. For example, if the deployment ratio is 0.2, it means that each floor has 8 ($= 0.2 \times 40$) Femto BSs on average, and each Femtocell block has $8 \times L$ Femto BSs. The deployment ratio can vary from 0.0 to 1.0. Moreover, a deployed Femto BS in an apartment may have two modes – activated or not. Thus another parameter

called “activation ratio” is introduced in this model, which is defined as the percentage of active Femto BSs. If a Femto BS is active, it will transmit with suitable power at traffic channels. Otherwise, the Femto BS will only transmit the control channels. Activation ratio can be from 0 to 100%. An example parameter table is shown in Table 6.1 [91].

For each Femtocell apartment, the Femto BS is randomly placed. It is assumed that there is one Femto UE per Femtocell, which is dropped randomly in each active Femtocell with a minimum separation of 20cm to the Femto BS.

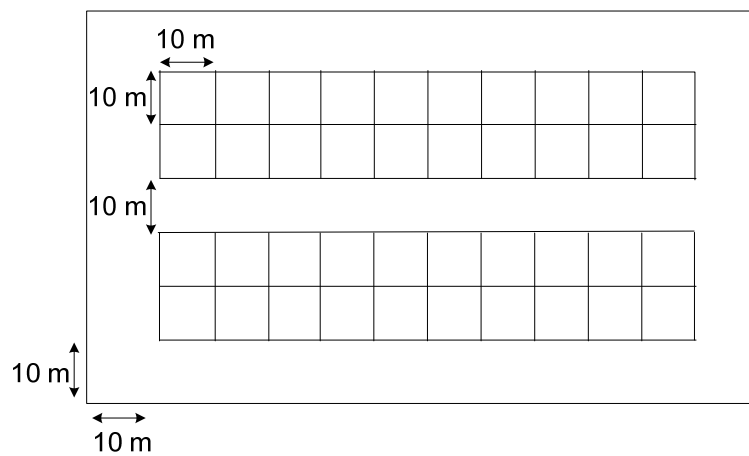


Figure 6.2 Femtocell block illustration

Table 6.1 An example of urban dense Femtocell modelling parameters

N (number of cells per row)	10
M (number of blocks per sector)	1
L (number of floors per block)	10
R (deployment ratio)	0.25
P (activation ratio)	50%

6.3 Problem Formulation for Resource Allocation

A two-tier OFDMA-based network that consists of an isolated Macrocell with dense Femtocell deployment is considered. The downlink resource allocation among Femtocells is studied. It is assumed that Femtocells are operating in locally available TVWS channels with the aid of Geo-location database introduced in Chapter 4 to avoid cross-tier interference between Femtocell and Macrocell. Therefore, the Femtocell tier co-channel interference is studied in this Chapter. Femtocells are assumed to operate in “closed access” mode, which restricts the use of Femtocells to users explicitly approved by owners. In the dense deployment scenario, conventionally each Femto BS accesses the same frequency spectrum, and therefore all the Femto BSs using the same sub-channels incur co-tier interference.

An example of co-tier interference in dense Femtocell deployment is illustrated in Figure 6.3. There are four Femto BSs in one floor of the building, and they are operating in the same sub-channels. In this case, the four Femto BSs produce severe co-channel interference to each other due to the close proximity among them. Considering Femto BSs in different floors that are operating in the same sub-channels, the co-channel interference problem would be more severe.

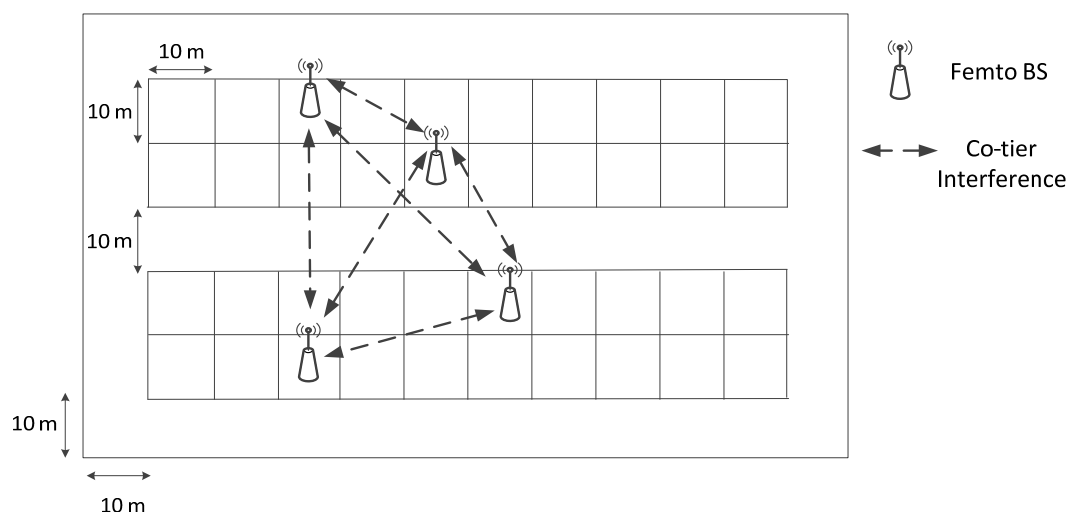


Figure 6.3 Illustration of co-tier interference among Femtocells in dense deployment scenario

In the dense Femtocell deployment scenario, assume that there are K Femto BSs and each serves one Femto UE. There are N sub-channels which can be accessed by all the Femto BSs and Femto UEs. The co-channel interference $I_{i,n}$ suffered by Femto UE i in sub-channel n can be expressed as:

$$I_{i,n} = \sum_{j=1, j \neq i}^K p_{j,n} g_{ij,n} \quad (6.1)$$

where $p_{j,n}$ is the transmit power of Femto BS j in sub-channel n . $g_{ij,n}$ is the channel gain between Femto BS j and Femto UE i in sub-channel n .

The Signal to Interference plus Noise Ratio (SINR) $\gamma_{i,n}$ of Femto UE i served by Femto BS i in sub-channel n can be expressed as:

$$\gamma_{i,n} = \frac{p_{i,n} g_{ii,n}}{\sigma_{i,n}^2 + I_{i,n}} \quad (6.2)$$

where $p_{i,n}$ is the transmit power of Femto BS i in sub-channel n . $g_{ii,n}$ is the channel gain between Femto BS i and Femto UE i in sub-channel n . While $\sigma_{i,n}^2$ is the power spectral density of additive white Gaussian noise in sub-channel n . In the right part of Equation (6.2), the numerator represents the received power of useful signal of Femto UE i , and the denominator represents the total power of interference signals from Femto BSs using the same sub-channel n , and the noise.

The capacity C_i of Femto UE i in sub-channel n can be calculated by using Shannon-Hartley theorem [106], as expressed in Equation (6.3), where ω is the bandwidth of sub-channel n .

$$C_{i,n} = \omega \log_2(1 + \gamma_{i,n}) \quad (6.3)$$

In this study, the idea of the resource allocation is to maximize the throughput of Femtocells, while limiting the co-tier interference suffered by Femto UEs, and guaranteeing the minimum SINR requirements of Femto UEs and power constraints. In the aim of reducing the interference suffered by Femto UEs, the Femto BSs tend to reduce their transmit power, so that the power consumption is reduced. According

to the discussion above, the resource allocation problem can be formulated as following:

Maximize:

$$\sum_{i=1}^K \sum_{n=1}^N C_{i,n} \quad (6.4a)$$

Subject to:

$$\sum_{i=1}^K \sum_{n=1}^N p_{j,n} g_{ij,n} < \delta_i, \quad \forall i \in \{1, 2, \dots, K\} \quad (6.4b)$$

$$\sum_{n=1}^N p_{i,n} < P_i^{max}, \quad \forall i \quad (6.4c)$$

$$\gamma_i \geq \gamma_i^{min}, \quad \forall i \quad (6.4d)$$

where δ_i represents the interference threshold level of Femto UE i . P_i^{max} is the maximum allowed transmit power of Femto BS i , and γ_i^{min} is the minimum SINR requirement of Femto UE i .

6.4 Power Efficient Resource Allocation Scheme

A power efficient resource allocation scheme is proposed for the resource allocation problem in dense Femtocell deployment, in order to maximize Femtocell throughput and limit the co-tier interference between Femtocells. In this study, it has been assumed that: 1) measurement reports are periodically performed by Femto UEs and then sent back to their Femto BSs; 2) these reports contain information of channel conditions from the their serving Femto BS and surrounding Femto BSs; and 3) the measurement information from different Femto BSs are gathered via the wired backhaul and processed in the central controller (e.g. Femtocell gateway), where the proposed scheme is performed.

The proposed scheme consists of the sub-channel allocation algorithm and the sub-channel power allocation algorithm being discussed in the following sections.

6.4.1 Sub-channel Allocation Algorithm

For the purpose of reducing potential co-channel interference among Femtocells, the sub-channel allocation is designed according to the interference avoidance rule, e.g. the reuse of an allocated sub-channel in a dense Femtocell deployment should produce as little as possible co-channel interference to Femto UEs using the same sub-channels.

Based on the information of Femto UEs' measurement reports on channel conditions from the their serving Femto BS and surrounding Femto BSs, central controller controls Femto BSs sub-channel allocation according to Equation (6.5).

For a Femto BS i allocates sub-channel to its Femto UE i , the sub-channel n among available sub-channels is chosen according to the following condition:

$$\min [\sum_{\substack{j=1 \\ j \neq i}}^K p_{i,n} g_{ji,n}], \quad \forall n \in N \quad (6.5)$$

where $p_{i,n}$ is the transmit power of Femto BS i in sub-channel n . $g_{ji,n}$ is the channel gain between Femto BS i and Femto UE j in sub-channel n . The equation means that for allocating resource to a Femto UE, among all available sub-channels, the chosen sub-channel is the one with the least sum of potential interference to all other Femto UEs using the same sub-channels.

6.4.2 Sub-channel Power Allocation Algorithm

6.4.2.1 Sub-channel Power Allocation Problem

After sub-channels are allocated to Femto UEs, power on sub-channels for each Femtocell should be allocated optimally. By applying the Lagrangian dual function for Equation (6.4), the optimization problem can be transformed as:

$$L(p_{i,n}, \lambda_i) = \sum_{i=1}^K \sum_{n=1}^N C_{i,n} - \sum_{i=1}^K \lambda_i^I \left(\sum_{\substack{j=1 \\ j \neq i}}^K \sum_{n=1}^N p_{j,n} g_{ij,n} - \delta_i \right) - \sum_{i=1}^K \lambda_i^P (\sum_{n=1}^N p_{i,n} - P_i^{max}) - \sum_{i=1}^K \lambda_i^S (\gamma_i^{min} - \gamma_i) \quad (6.6)$$

where $\lambda_i = [\lambda_i^I, \lambda_i^P, \lambda_i^S]$ is the set of Lagrangian multipliers. λ_i^I, λ_i^P and λ_i^S are the Lagrangian multipliers for interference, transmit power and SINR constraint functions, respectively. Equation (6.6) can be reordered to obtain:

$$L(p_{i,n}, \lambda_i) = \sum_{n=1}^N L_n(p_{i,n}, \lambda_i) \quad (6.7)$$

where

$$L_n(p_{i,n}, \lambda_i) = \sum_{i=1}^K C_i - \sum_{i=1}^K \lambda_i^I (\sum_{\substack{j=1 \\ j \neq i}}^K p_{j,n} g_{ij,n} - \delta_{i,n}) - \sum_{i=1}^K \lambda_i^P (p_{i,n} - P_{i,n}^{max}) - \sum_{i=1}^K \lambda_i^S (\gamma_{i,n}^{min} - \gamma_{i,n}) \quad (6.8)$$

This way the original problem splits into N sub-problems. Each sub-problem focuses on one sub-channel. So a single channel scenario can be solved first and then extend the solution to the N channel case. Thus the optimization problem is re-defined as:

Maximize:

$$\sum_{i=1}^K C_i \quad (6.9a)$$

Subject to:

$$\sum_{\substack{j=1 \\ j \neq i}}^K p_j g_{ij} < \delta'_i, \quad \forall i \in \{1, 2, \dots, K\} \quad (6.9b)$$

$$p_i < P_i^{max'}, \quad \forall i \quad (6.9c)$$

$$\gamma_i \geq \gamma_i^{min'}, \quad \forall i \quad (6.9d)$$

where δ'_i is the interference threshold for Femto UE i in a sub-channel n , $P_i^{max'}$ and $\gamma_i^{min'}$ are the maximum transmit power and minimum SINR requirement for Femto UE i in a sub-channel n , respectively.

6.4.2.2 Sequential Quadratic Programming Solution

Equation (6.9) is a non-linear optimization problem which would generally be NP-hard to solve. In this study, the SQP method is used to solve this problem. The SQP method is an iterative approach to solve the non-linear optimization problem. In each iteration, the solution to the non-linear problem is calculated using a quadratic approximation [89]. For example, the K^{th} iteration is formulated by a quadratic programming sub-problem. The solution of the K^{th} iteration $\mathbf{p}^k = [p_1^k, p_2^k, \dots, p_K^k]^T$ is then used to construct a better approximation through an updating process, which is \mathbf{p}^{k+1} , for the $(K + 1)^{th}$ iteration. The process repeats until the convergence criteria are met.

Firstly, the initial approximation of the solution is defined as $\mathbf{p}^0 = [p_1^0, p_2^0, \dots, p_K^0]^T$. Then to define the problem in SQP format, let $\mathbf{c}(\mathbf{p}) = [\mathbf{c}^I(\mathbf{p}) \mathbf{c}^P(\mathbf{p}) \mathbf{c}^S(\mathbf{p})]^T$, where $\mathbf{c}^I(\mathbf{p}) = [c_1^I(\mathbf{p}) c_2^I(\mathbf{p}) \dots c_K^I(\mathbf{p})]^T$, $\mathbf{c}^P(\mathbf{p}) = [c_1^P(\mathbf{p}) c_2^P(\mathbf{p}) \dots c_K^P(\mathbf{p})]^T$, $\mathbf{c}^S(\mathbf{p}) = [c_1^S(\mathbf{p}) c_2^S(\mathbf{p}) \dots c_K^S(\mathbf{p})]^T$, and $\mathbf{c}^I(\mathbf{p})$, $\mathbf{c}^P(\mathbf{p})$, $\mathbf{c}^S(\mathbf{p})$ are the vectors of interference, transmit power and SINR constraint functions respectively, where

$$c_i^I(\mathbf{p}) = \sum_{j=1, j \neq i}^K p_j g_{ij} - \delta_i' \quad (6.10a)$$

$$c_i^P(\mathbf{p}) = p_i - P_i^{max'} \quad (6.10b)$$

$$c_i^S(\mathbf{p}) = \gamma_i^{min'} - \gamma_i \quad (6.10c)$$

The Jacobian matrix of $\mathbf{c}(\mathbf{p})$ is denoted as $\mathbf{A}(\mathbf{p})$, which is defined as the matrix of all first-order partial derivatives of $\mathbf{c}(\mathbf{p})$.

$$\mathbf{A} = \frac{\partial(\mathbf{c})}{\partial(p_1, \dots, p_K)} \quad (6.11)$$

The Lagrangian function for Equation (6.9a) subject to Equation (6.9b), (6.9c) and (6.9d) is given by:

$$\begin{aligned} L(\mathbf{p}, \boldsymbol{\lambda}) = & \sum_{i=1}^K C_i - \sum_{i=1}^K \lambda_i^I \left(\sum_{j=1, j \neq i}^K p_j g_{ij} - \delta_i' \right) \\ & - \sum_{i=1}^K \lambda_i^P (p_i - P_i^{max'}) - \sum_{i=1}^K \lambda_i^S (\gamma_i^{min'} - \gamma_i) \end{aligned} \quad (6.12)$$

where $\boldsymbol{\lambda} = [\boldsymbol{\lambda}^I, \boldsymbol{\lambda}^P, \boldsymbol{\lambda}^S]$. $\boldsymbol{\lambda}^I = [\lambda_1^I, \lambda_2^I \dots \lambda_K^I]^T$, $\boldsymbol{\lambda}^P = [\lambda_1^P, \lambda_2^P \dots \lambda_K^P]^T$ and $\boldsymbol{\lambda}^S = [\lambda_1^S, \lambda_2^S \dots \lambda_K^S]^T$ are the vectors of Lagrangian multipliers.

The Hessian matrix $\mathbf{H}(\mathbf{p}, \boldsymbol{\lambda})$ of this optimization problem is then defined, which is the square matrix of second-order partial derivatives of the Lagrangian function. Its elements can be represented as:

$$[H]_{i,j} = \frac{\partial^2 L(\mathbf{p}, \boldsymbol{\lambda})}{\partial p_i \partial p_j}, \quad i, j \in \{1, 2, \dots, K\} \quad (6.13)$$

The first-order optimality condition for the Lagrangian function (6.12) is [85]:

$$\nabla L(\mathbf{p}, \boldsymbol{\lambda}) = 0 \quad (6.14)$$

To solve Equation (6.14), in each iteration k , the SQP method improves the estimate solution $(\mathbf{p}^k, \boldsymbol{\lambda}^k)$ to (6.14) with a corrections vector $\mathbf{s} = [(\mathbf{s}^k)^T (\boldsymbol{\lambda}^k)^T]^T$. The corrections vector \mathbf{s} can be obtained by solving the following quadratic programming sub-problem:

$$\text{Minimise: } \frac{1}{2} \langle \mathbf{s}, \mathbf{H}^k \mathbf{s} \rangle + \langle \mathbf{g}_L(\mathbf{p}^k), \mathbf{s} \rangle \quad (6.15a)$$

$$\text{Subject to: } \mathbf{A}(\mathbf{p}^k) \mathbf{s} + \mathbf{c}(\mathbf{p}^k) \geq 0 \quad (6.15b)$$

where $\langle \rangle$ indicates the operation: $\langle \mathbf{x}, \mathbf{y} \rangle = \sum_{l=1}^M x_l y_l$, for $\mathbf{x}, \mathbf{y} \in R^M$, $\mathbf{H}^k = \mathbf{H}(\mathbf{p}^k, \boldsymbol{\lambda}^k)$, and $\mathbf{g}_L(\mathbf{p}^k)$ is the gradient of the Lagrangian function in Equation (6.12), and $\mathbf{g}_L = [g_{L_1}, g_{L_2} \dots g_{L_K}]^T$, where

$$g_{L_i} = \frac{\omega}{\ln 2} \left(\frac{g_{ii}}{\sigma_i^2 + \sum_{j=1}^K p_j g_{ij}} - \sum_{\substack{j=1 \\ j \neq i}}^K \frac{p_j g_{jj}^2}{\left(\sigma_j^2 + \sum_{\substack{l=1 \\ l \neq j}}^K p_l g_{jl} \right) \left(\sigma_j^2 + \sum_{l=1}^K p_l g_{jl} \right)} \right) - \sum_{\substack{j=1 \\ j \neq i}}^K \lambda_j^I g_{ji} - \lambda_i^P + \frac{\lambda_i^S g_{ii}}{\sigma_i^2 + \sum_{j=1}^K p_j g_{ij}} - \sum_{\substack{j=1 \\ j \neq i}}^K \frac{\lambda_j^S p_j g_{jj} g_{ji}}{\left(\sigma_j^2 + \sum_{\substack{l=1 \\ l \neq j}}^K p_l g_{jl} \right)^2} \quad (6.16)$$

The solution to the quadratic programming sub-problem in Equation (6.15) can be obtained by solving the following equation:

$$\begin{bmatrix} \mathbf{H}^k & \mathbf{A}^T \\ \mathbf{A} & 0 \end{bmatrix} \times \begin{bmatrix} \mathbf{s}^k \\ -\mathbf{s}_\lambda^k \end{bmatrix} = - \begin{bmatrix} \mathbf{g}_L(\mathbf{p}^k) \\ \mathbf{c}(\mathbf{p}^k) \end{bmatrix} \quad (6.17)$$

Then the obtained solution corrections vector $\mathbf{s} = [(\mathbf{s}^k)^T (\mathbf{s}_\lambda^k)^T]^T$ can be used to update the current estimation solution $(\mathbf{p}^k, \boldsymbol{\lambda}^k)$, including the power allocation estimation and Lagrangian multipliers estimation as follows:

$$\begin{bmatrix} \mathbf{p}^{k+1} \\ \boldsymbol{\lambda}^{k+1} \end{bmatrix} = \begin{bmatrix} \mathbf{p}^k + \alpha^k \mathbf{s}^k \\ \boldsymbol{\lambda}^k + \beta^k \mathbf{s}_\lambda^k \end{bmatrix} \quad (6.18)$$

where α^k and β^k are non-negative step sizes.

The values of step sizes used in the updating process are chosen according to the progress of converging towards the solution point. This progress is monitored by a merit function ϕ . Merit function assesses the quality of the “search direction” and ensures that the iterations are working in the right direction towards the solution point. The selection of the set of step sizes is performed towards the direction of reducing the value of merit function, such that $\phi(\mathbf{p}^k + \alpha^k \mathbf{s}^k)$ is sufficiently smaller than $\phi(\mathbf{p}^k)$. In the proposed scheme, a ‘back-tracking’ method is used. ‘back-tracking’ is a procedure of trying successively smaller step size values until a suitable step size is obtained. In general, the step size of the power allocation α^k is set by ‘back-tracking’ method, while the step size β^k of the Lagrangian multipliers is set to the value of α^k .

The augmented Lagrangian penalty function is used as the merit function [85]:

$$\phi(\mathbf{p}, \boldsymbol{\eta}) = \sum_{i=1}^K \omega \log_2(1 + \gamma_i) + \mathbf{c}(\mathbf{p})^T \mathbf{u}^-(\mathbf{p}) + \frac{\eta}{2} \|\mathbf{c}(\mathbf{p})\|_2^2 \quad (6.19)$$

where $\|\cdot\|_2$ represents the second-order norm and η is a constant to be chosen, and

$$\mathbf{u}^-(\mathbf{p}) = -[\mathbf{A}(\mathbf{p})^T \mathbf{A}(\mathbf{p})]^{-1} \mathbf{A}(\mathbf{p})^T \nabla \times (\sum_{i=1}^K \omega \log_2(1 + \gamma_i)) \quad (6.20)$$

Equation (6.20) can also be used to calculate the initial estimation of the Lagrangian multipliers $\boldsymbol{\lambda}^0 = [\lambda_1^0, \lambda_2^0, \dots, \lambda_K^0]^T$, by $\boldsymbol{\lambda}^0 = \mathbf{u}^-(\mathbf{p}^0)$, if given the initial power allocation estimation $\mathbf{p}^0 = [p_1^0, p_2^0, \dots, p_K^0]^T$.

The convergence criterion for the SQP method used in the proposed scheme is as follows [107]:

$$\|\mathbf{c}_k\| + \|\mathbf{g}_L(\mathbf{p}^k) - \mathbf{A}_k^T\| \leq \varepsilon \quad (6.21)$$

where ε is a chosen constant.

Finally, using the SQP method to solve the sub-channel power allocation problem can be summarized as follows:

Assume that the initial point is $(\mathbf{p}^0, \boldsymbol{\lambda}^0)$ and merit function is $\phi(\mathbf{p})$. The number of iteration is denoted as k , which starts from 0.

- 1) Construct the Lagrangian function (6.12) for the target optimization problem.
- 2) Construct and solve Equation (6.15) to obtain the corrections vector $\mathbf{s} = [(\mathbf{s}^k)^T (\mathbf{s}_\lambda^k)^T]^T$.
- 3) Calculate the step size of the power allocation α^k using the 'back-tracking' method and ensuring the direction of reducing the value of the chosen merit function.
- 4) Update the power allocation estimation and the Lagrangian multipliers estimation using obtained step sizes and correction vectors according to Equation (6.18).
- 5) Stop the iterations if convergence criterion is met; otherwise, set $k = k + 1$, and then go to step 1 for the next iteration.

6.4.3 Power Efficient Resource Allocation Scheme Procedure

The procedure of the proposed power efficient resource allocation scheme can be summarized as in Table 6.2.

Table 6.2 Procedure of the proposed power efficient resource allocation scheme

<p>Sub-channel Allocation</p> <ol style="list-style-type: none"> 1. Every Femto UE i sends the measurement report to Femto FBs, the report contains channel information and processed in central controller for resource allocation. 2. Femto BSs firstly allocate all sub-channels to Femto UEs in a round-robin manner. 3. Then Femto BSs allocate the co-channel sub-channels to Femto UEs, according to the rule $\min [\sum_{j \neq i}^K p_{j,n} g_{ji,n}]$, which means that the allocated sub-channel n to a Femto UE i is the one with the least sum of potential interference to all other Femto UEs using same sub-channel n. <p>Sub-channel Power Allocation</p> <ol style="list-style-type: none"> 4. After sub-channel allocation, sub-channel power allocation problem is constructed in the central controller. Initial power for each sub-channel is set and SQP method is used to solve the problem. 5. According to the SQP method solutions, each Femto BS updates its power allocation on each sub-channel.

6.5 Simulation Results and Analysis

The proposed scheme is evaluated by a two-tier OFDMA Femtocell simulator with dense deployment as described in section 3.3. The simulation parameters adopted are introduced in section 3.3.4. Without loss of generality, one Femtocell block consisting of L floors is assumed, where L is chosen as 10. Each active Femto BS serves one Femto UE, and a Femto BS allocates one sub-channel to its Femto UE in each Transmission Time Interval (TTI).

The simulations run for a full-buffer traffic model, which means all users in the system are active simultaneously. Each run of the simulation is iterated over a series of snapshots to obtain statistically accurate results. Moreover, the users in the system are assumed to be static for the duration of the snapshot. Perfect synchronization in both time and frequency is assumed, so that interference between adjacent sub-channels can be neglected.

To benchmark the performance of the proposed power efficient resource allocation scheme, a graph-based resource allocation scheme for co-channel interference mitigation in dense Femtocell deployment introduced in paper [29] is implemented. In the scheme, the interference graph of Femtocells is firstly generated based on the measured SINR of Femtocells, and then sub-channels which are not being used by neighbouring Femtocells are allocated to target Femtocells accordingly. A traditional fix power resource allocation scheme is also implemented, where Femto BSs allocate power equally on each sub-channel. It is the current practice used in various Femto BSs and implemented as a reference to be compared with the proposed scheme.

Figure 6.4 shows network layout in the simulation. In the diagram, the black triangle represents the Macro BS, while small green circles in Femtocell blocks represent the Femto BSs. Red points represent Femto UEs. Femto BSs and Femto UEs are distributed in different floors but are shown as in the same 2D plane in Figure 6.4.

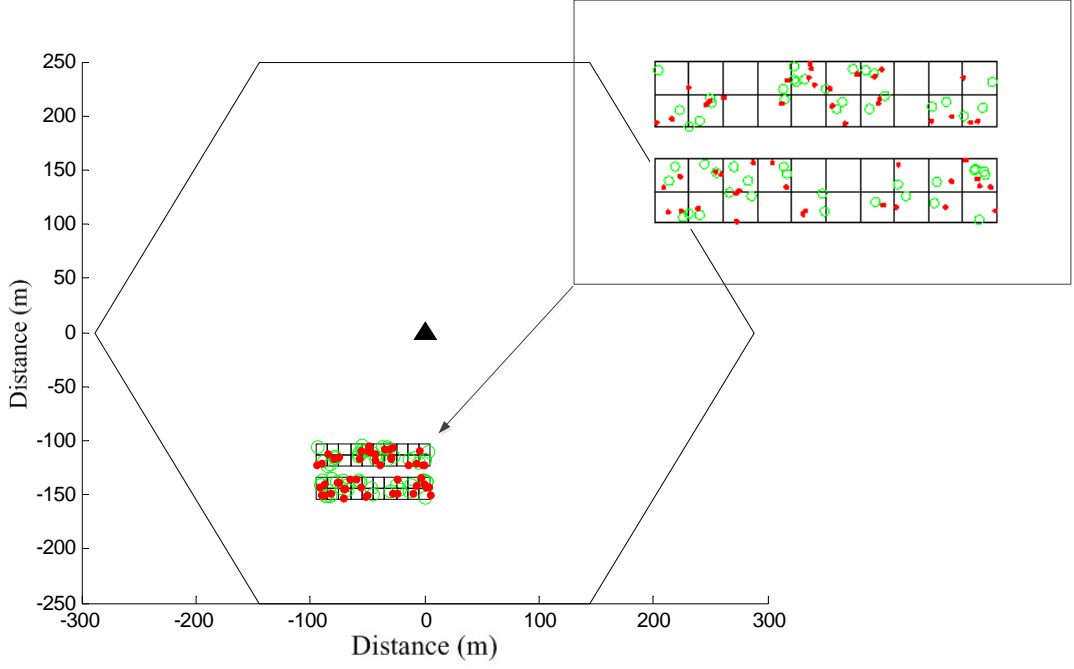


Figure 6.4 Network layout in simulation

The downlink co-tier interference mitigation performance of the proposed power efficient resource allocation scheme (named Power Efficient) is compared with the graph based resource allocation scheme (named Graph) and the fix power resource allocation scheme (named Fix Power). In Figure 6.5, the blue line represents the proposed Power Efficient scheme. While the green line represents the Graph scheme, and the red line represents the Fix Power scheme. As it can be seen from the diagram, when using the Power Efficient scheme the total interference suffered by Femto UEs can be reduced for more than 3dB at the 50th percentile of the CDF diagram in comparison with the Graph scheme, and for more than 12dB in comparison with the Fix Power scheme. This demonstrates that the proposed Power Efficient scheme is better in reducing co-tier interference among Femtocells than the other two schemes.

Figure 6.6 compares the total throughput of Femto UEs between the three schemes. According to the simulation results, the total throughputs are 8.78×10^7 , 10.03×10^7 and 10.15×10^7 bit/s at the 50th percentile of the CDF diagram for Fix Power, Graph and Power Efficient schemes, respectively. The proposed Power Efficient scheme achieves more than 15% throughput than the Fix Power scheme, and also is slightly better than the Graph scheme.

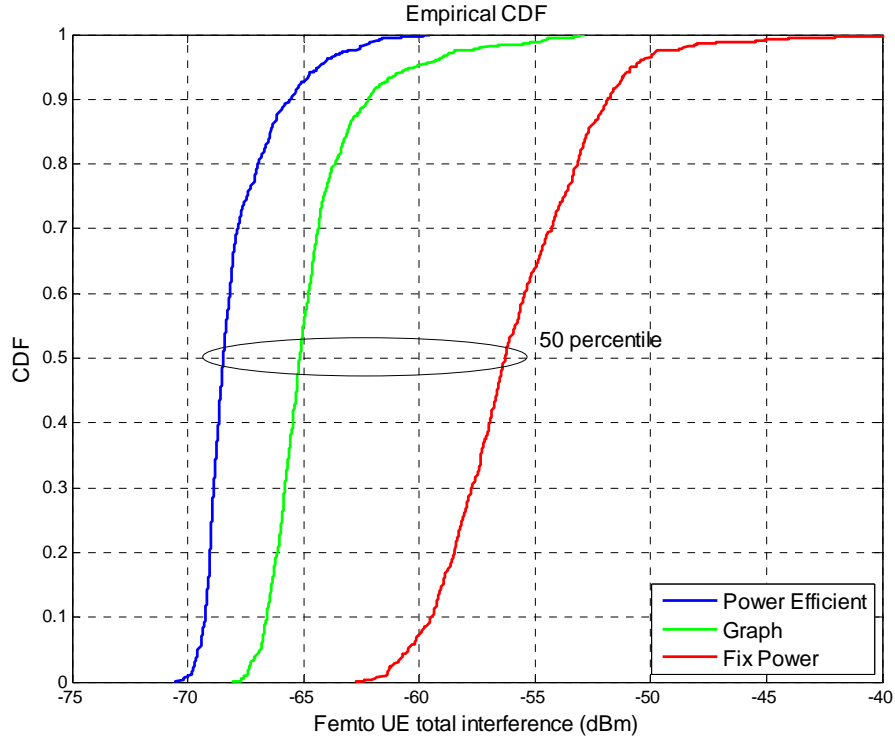


Figure 6.5 Femto UE total co-tier interference comparison

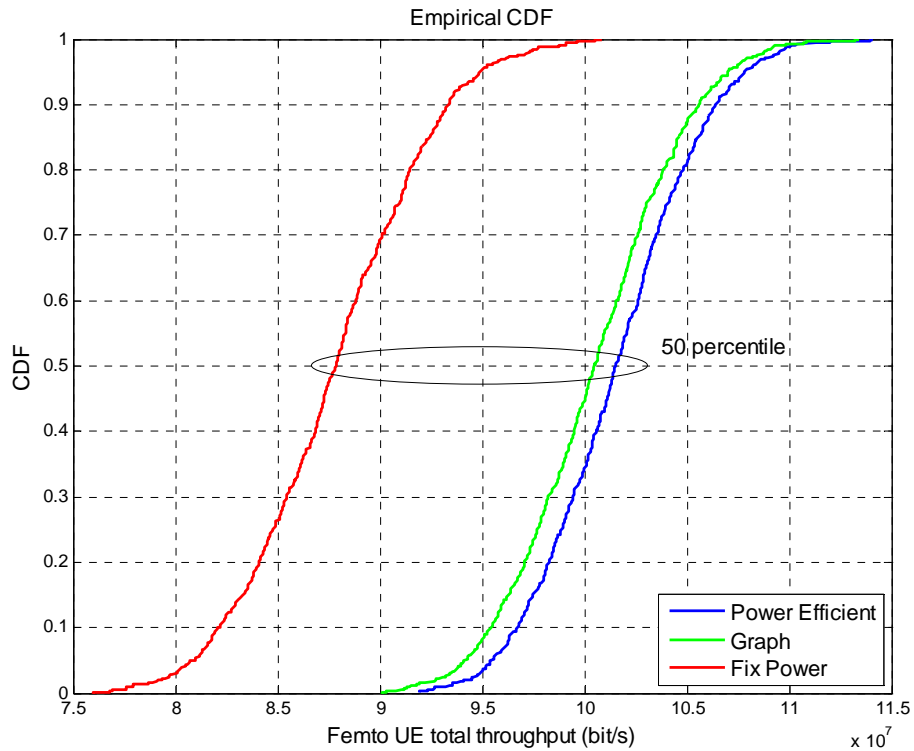


Figure 6.6 Femto UE total throughput comparison

The power consumption comparison of the three schemes is presented in Figure 6.7. The power consumption of Power Efficient scheme is about 126mW at the 50th

percentile, and that of Fix Power and Graph scheme is 200mW (Note that the CDFs of Fix Power and Graph are superposed). This means that the power consumption of the proposed scheme is 37% less than the other two schemes, which proves that the proposed scheme achieves higher throughput at the expense of less power consumption.

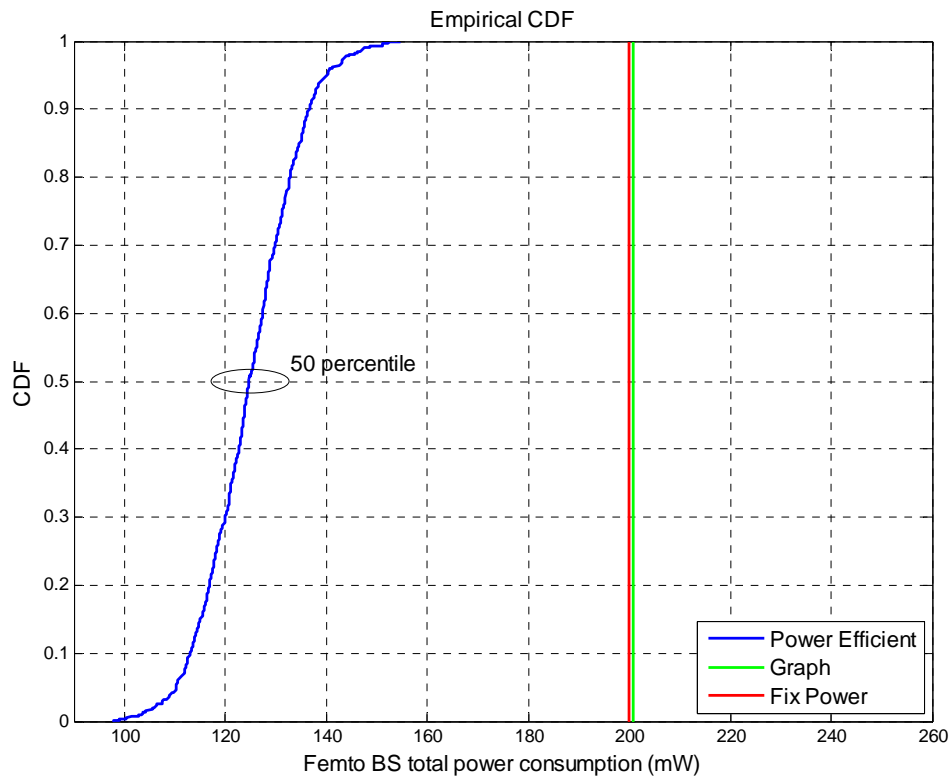


Figure 6.7 Femto UE total power consumption comparison

The energy efficiency of the three schemes is also investigated. The energy efficiency is defined as throughput per transmitted power (bits/s/mW). As shown in Figure 6.8, the energy efficiency of proposed Power Efficient scheme is about 8.12×10^5 bit/s/mW at the 50th percentile in the CDF diagram, which is about 1.6 times of the Graph scheme (e.g. 5.02×10^5 bit/s/mW) and 1.8 times of the Fix Power scheme (e.g. 4.39×10^5 bit/s/mW). This is because the proposed scheme takes into consideration Femto UE's interference in the maximization of throughput. Hence, it can achieve high throughput at the expense of much lower power consumption. This result demonstrates that the proposed power efficient scheme is a strong candidate for green communications.

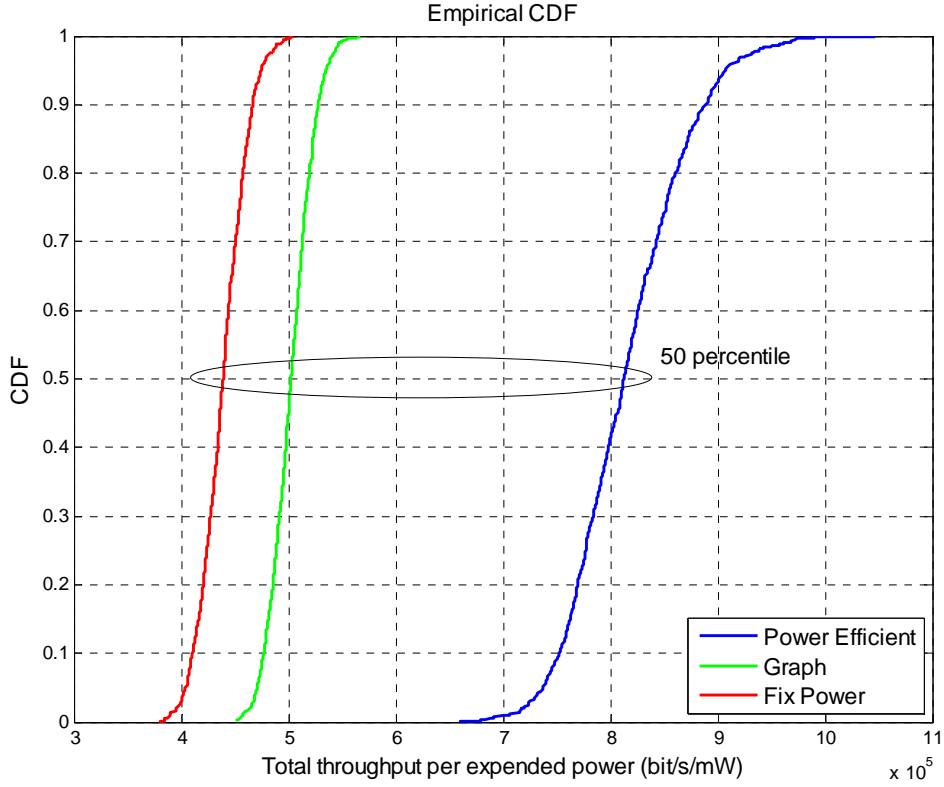


Figure 6.8 Power efficiency comparison

The SQP method used in the proposed sub-channel power allocation algorithm is a ‘globally convergent’ optimization method [85]. It means that the performance of the proposed scheme should not be affected greatly by the choice of initial power allocation $\mathbf{p}^0 = [p_1^0, p_2^0, \dots, p_k^0]^T$. In order to verify this property of the proposed scheme, various values of initial sub-channel power allocation adopted in SQP method are chosen from 0mW to 4mW. Corresponding system throughput and power consumption performance are investigated. As shown in Figure 6.9 and Figure 6.10, the blue lines with triangles indicate the proposed Power Efficient scheme (Note that the CDFs of Fix Power and Graph schemes are superposed in Figure 6.10). When initial power allocation in SQP method is set from 0mW to 4mW, the choice of different initial power allocation settings have similar performance in terms of total throughput and total power consumption. Variations exist but are negligibly. These results are consistent with the ‘globally convergent’ property of SQP method.

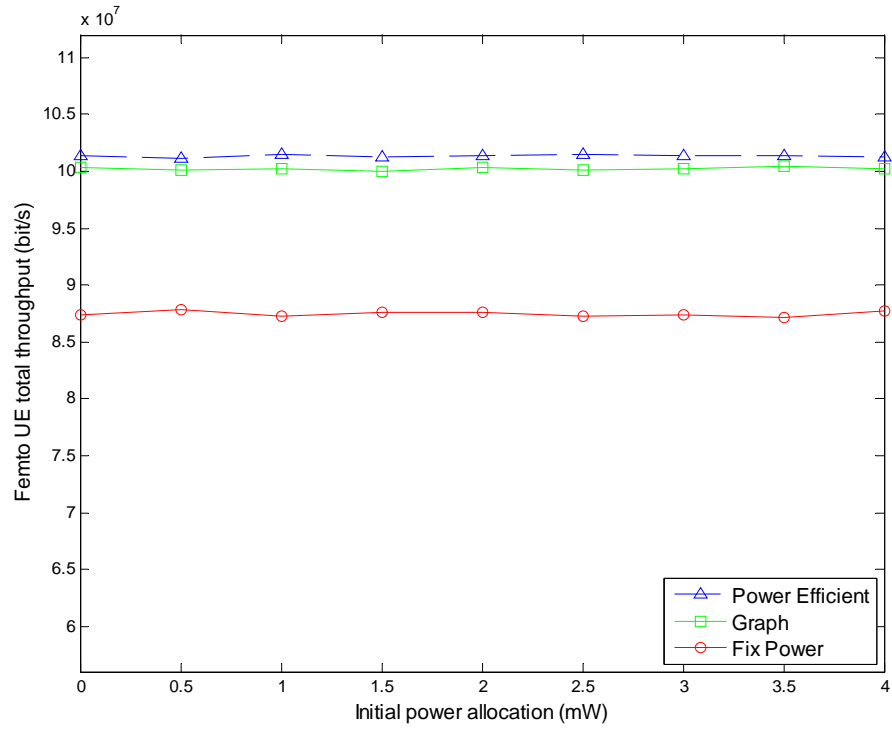


Figure 6.9 Femto UE total throughput comparison with different initial power allocation settings in the proposed power efficient scheme

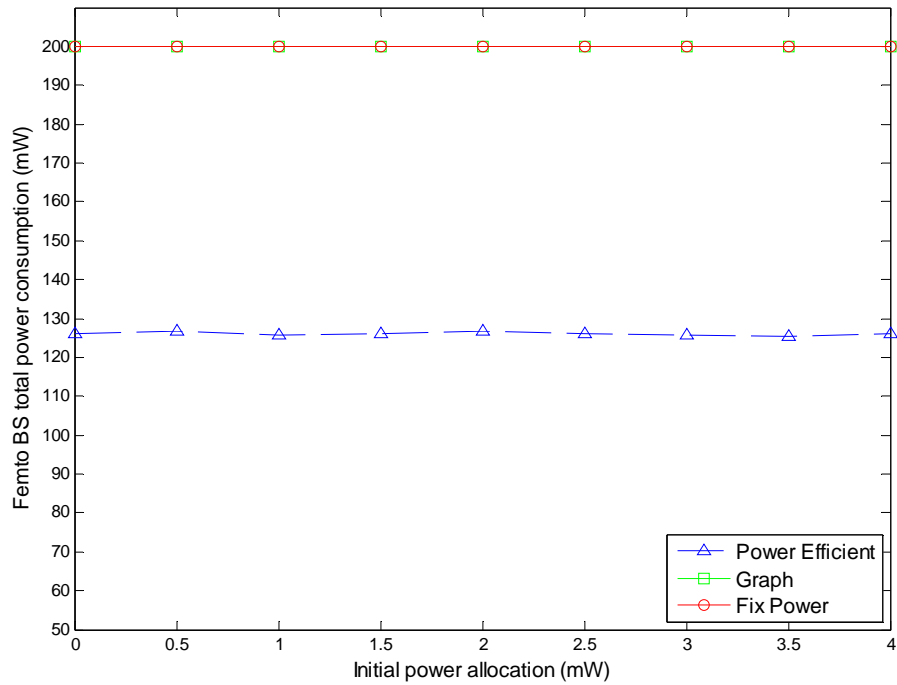


Figure 6.10 Femto BS total power consumption comparison with different initial power allocation settings in the proposed power efficient scheme

6.6 Summary

In this chapter, a power efficient resource allocation scheme was proposed for dense Femtocell deployment scenario with a target of maximizing the throughput of Femtocells while limiting co-tier interference between Femtocells, and guaranteeing the minimum SINR requirement of Femto UEs. The proposed resource allocation scheme consisted of the sub-channel allocation algorithm and the sub-channel power control algorithm. The sub-channel power allocation was formulated as a nonlinear optimization problem, and was solved by the SQP method.

Simulation results have shown that the proposed scheme reduced more than 3dB and 12dB downlink co-tier interference than those of the graph based scheme and the fix power scheme in the dense Femtocell deployment scenario. The proposed scheme has also achieved 15% more throughput than the fix power scheme, while consumes 37% less power at the same time.

Conclusions can be drawn from the results that the proposed scheme has high energy efficiency in terms of throughput per expended power, which makes it a strong candidate for green communications. Moreover, different initial power allocation settings have similar performance in terms of total throughput and power consumption. These results are consistent with the ‘globally convergent’ property of SQP method, and demonstrate the robustness of the SQP method.

Chapter 7 Conclusions and Future Work

7.1 Conclusions

This thesis presents research on interference mitigation in Femtocell networks, which is the most widely deployed type of small cells. In the downlink of traditional Femtocell networks, there exists cross-tier interference between Femtocell and Macro UEs, and co-tier interference between Femtocells. Existing approaches are based on the licensed cellular frequency band, and have limited performance improvement at the expense of spectrum resource. This thesis proposed a Geo-location database method to obtain locally available TVWS information, and designed corresponding resource allocation schemes utilizing TVWS to mitigate interference in practical Femtocell deployment scenarios, e.g. cross-tier interference in suburban Femtocell deployment, and co-tier interference in dense Femtocell deployment.

In Chapter 4, a Geo-location database model using power control method to obtain locally available TVWS information was presented. This database has taken into account DTV transmitter information in UK published by Ofcom and regulations on unlicensed use of TVWS. By inputting the location of TVWS-based CR devices, the database can return locally available TVWS channel information and associated maximum allowable transmit power. Therefore, it can be used as an effective approach to obtaining locally available TVWS information. The proposed Geo-location database has been compared and verified with a keep-away region database model and an existing DTV transmitter database from Digital UK.

According to the results it can be concluded that the proposed power-control database model was an effective cognitive access method to obtain TVWS information, and was more efficient in obtaining TVWS information than the keep-away region model, as more available TVWS channels can be obtained with various maximum allowable transmit power.

Based on the available TVWS, a grid-based plus interference avoidance resource allocation scheme was proposed for a simplified Femtocell network to investigate the system performance of using TVWS in Femtocell networks. In the proposed scheme, available TVWS channel list was assigned to Femto BSs based on their grid locations, and the avoidance of possible co-channel interference between Femtocells was also considered. According to the simulation results conclusions can be drawn that deploying Femtocells that are using TVWS in Macrocell network is an effective way to increase the system throughput, and the incurred throughput gain is getting higher as the number of deployed Femtocells increases.

In Chapter 5, a novel system architecture of using TVWS was proposed for cross-tier interference mitigation in suburban Femtocell deployment. The architecture included the previously proposed Geo-location database model and a novel resource allocation scheme using locally available TVWS. The proposed scheme has been designed to avoid Femtocells interference on nearby Macro UEs by allocating locally available TVWS spectrum resource to those interfering Femtocells.

The proposed architecture exemplifies a practical system model that makes use of TVWS in resource allocation in Femtocell networks, by combining the Geo-location database model as the cognitive access method to TVWS and the resource allocation scheme that can allocate TVWS resources. The proposed system architecture can also be referred as an example in designing other cognitive radio systems that are based on Geo-location database to obtain target spectrum information for secondary use.

The proposed architecture was investigated in the suburban area scenario. Simulation results showed that the proposed architecture can reduce the downlink interference suffered by Macro UEs by about 4.5dB and 3.5dB at the 70th percentile of the CDF diagram in comparison with the traditional All-shared scheme and the DRP scheme, respectively. The impacts on the system performance of choosing different SINR thresholds were also discussed. An appropriate SINR threshold value of -8dB in the proposed scheme has been identified by considering both of the performance and cost.

Conclusions can be drawn from the obtained results that the proposed scheme performed better in the scenarios of more dense Femtocell distribution or smaller Macrocell, and is better in providing higher SINR for MUEs in the cell edge area than the traditional scheme. These conclusions are worth to be considered when implementing different resource allocation schemes in Femtocells deployment.

In Chapter 6, a power efficient resource allocation scheme was proposed for co-tier interference mitigation in dense Femtocell deployment. This scheme aimed at maximizing the throughput of Femtocells while limiting the co-tier interference among Femtocells. In the proposed scheme, the sub-channel allocation was designed to reduce potential co-channel interference. The sub-channel power allocation was formulated as a nonlinear optimization problem, and was solved by the SQP method iteratively. Simulation results showed that the proposed power efficient scheme can reduce more than 3dB and 12dB downlink interference suffered by Femto UEs in comparison with those of the graph based scheme and traditional fix power scheme, respectively. Moreover, the proposed scheme achieved 15% more throughput than the fix power scheme, while consumed 37% less power at the same time.

It can be concluded that the proposed scheme can not only increase the system throughput, while reducing the co-tier interference suffered by Femto UEs, but also consume much less power. Considering the energy saving has become an important issue in current communications, these advantages make the proposed scheme a strong candidate for green communications.

7.2 Future work

In this thesis, the designed Geo-location database is for obtaining locally available TVWS information. In CR systems, Geo-location database is an effective approach for assessing spectrum opportunities for secondary use. In the future work, the current database can be further investigated for obtaining available resource information in other spectrum band as well. This can be achieved by updating the database with usage information of other spectrum band and corresponding primary service

protection requirements. In this way, Femtocells can get more available spectrum resource to use.

Furthermore, the interference mitigation study of Femtocells in a single Macrocell can be further extended to a multi-cell cellular network scenario. The simulator can be extended to implement the multi-cell cellular network structure. Based on that, proposed resource allocation schemes can be further investigated to adapt to more complex interference mitigation situations, including inter-cell interference between Macrocells. It is also worth to extend the result of this research by taking into consideration different user traffic types and service requirements in designing the resource allocation schemes, in order to tackle different services provided in Femtocell networks.

References

- [1] V. Chandrasekhar, J. G. Andrews, and A. Gatherer, "Femtocell networks: a survey," *IEEE Communications Magazine*, vol. 46, no. 9, pp. 59-67, September 2008.
- [2] Small Cell Forum, "Release one: Home," February 2013.
- [3] A. A. M. Saleh, A. J. Rustako, and R. S. Roman, "Distributed antennas for indoor radio communications," *IEEE Transactions on Communications*, vol. 35, no. 12, pp. 1245-1251, December 1987.
- [4] C.-L. I, L. J. Greenstein, and R. D. Gitlin, "A microcell/macrocell cellular architecture for low- and high-mobility wireless users," *IEEE Journal on Selected Areas in Communications*, vol. 11, no. 6, pp. 885-891, August 1993.
- [5] Small Cell Forum, White Paper, "Small Cell Market Status," February 2013.
- [6] H. Claussen, L. T. W. Ho, and L. G. Samuel, "An overview of the femtocell concept," *Bell Labs Technical Journal*, vol. 13, no. 1, pp. 221-246, March 2008.
- [7] N. Saquib, E. Hossain, L. B. Le, and D. I. Kim, "Interference management in OFDMA femtocell networks: issues and approaches," *IEEE Wireless Communications*, vol. 19, no. 3, pp. 86-95, June 2012.
- [8] S. Kawade and M. Nekovee, "Can cognitive radio access to TV White Spaces support future home networks?," *2010 IEEE Symposium on New Frontiers in Dynamic Spectrum*, pp. 1-8, 6-9 April 2010.
- [9] Ofcom, "Statement on cognitive access to interleaved spectrum," 1 July 2009.

- [10] T. Zahir, K. Arshad, A. Nakata, and K. Moessner, "Interference management in femtocells," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 1, pp. 293-311, First Quarter 2013.
- [11] S. S. Prasad and R. Baruah, "Femtocell mass deployment: Indian perspective," *3rd International Conference on Anti-counterfeiting, Security, and Identification in Communication (ASID)*, pp. 34-37, 20-22 August 2009.
- [12] M. Neruda, J. Vrana, and R. Bestak, "Femtocells in 3G mobile networks," *16th International Conference on Systems, Signals and Image Processing (IWSSIP)*, pp. 1-4, 18-20 June 2009.
- [13] H. Holma and A. Toskala, *LTE for UMTS - OFDMA and SC-FDMA Based Radio Access*, John Wiley & Sons, 2009.
- [14] D. Lopez-Perez, A. Valcarce, G. D. L. Roche, and J. Zhang, "OFDMA femtocells: A roadmap on interference avoidance," *IEEE Communications Magazine*, vol. 47, no. 9, pp. 41-48, September 2009.
- [15] Wireless Design and Development Website, <http://www.wirelessdesignmag.com/>, retrieved on 29 August 2011.
- [16] G. Gür, S. Bayhan, and F. Alagoz, "Cognitive femtocell networks: An overlay architecture for localized dynamic spectrum access," *IEEE Wireless Communications*, vol. 17, no. 4, pp. 62-70, August 2010.
- [17] J. Xiang, Y. Zhang, T. Skeie, and L. Xie, "Downlink spectrum sharing for cognitive radio femtocell networks," *IEEE Systems Journal*, vol. 4, no. 4, pp. 524-534, December 2010.
- [18] FCC, "Public Notice, ET Docket no. 04-186, Office of Engineering and Technology Invites Proposals from Entities Seeking to be Designated TV Band Device Database Managers," November 2009.
- [19] D. Lopez-Perez, A. Valcarce, G. D. L. Roche, E. Liu, and J. Zhang, "Access

- methods to WiMAX femtocells: A downlink system-level case study," *11th IEEE Singapore International Conference on Communication Systems (ICCS)*, pp. 1657-1662, 19-21 November 2008.
- [20] G. D. L. Roche, A. Valcarce, D. Lopez-Perez, and J. Zhang, "Access control mechanisms for femtocells," *IEEE Communications Magazine*, vol. 48, no. 1, pp. 33-39, January 2010.
- [21] A. Golaup, M. Mustapha, and L. B. Patanapongpibul, "Femtocell access control strategy in UMTS and LTE," *IEEE Communications Magazine*, vol. 47, no. 9, pp. 117-123, September 2009.
- [22] S. Lee, "An enhanced IEEE 1588 time synchronization algorithm for asymmetric communication link using block burst transmission," *IEEE Communications Letters*, vol. 12, no. 9, pp. 687-689, September 2008.
- [23] A. Valcarce, D. Lopez-Perez, G. D. L. Roche, and J. Zhang, "Limited access to OFDMA femtocells," *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 1-5, 13-16 September 2009.
- [24] T. Chiba and H. Yokota, "Efficient route optimization methods for femtocell-based all IP networks," *IEEE International Conference on Wireless and Mobile Computing, Networking and Communications*, pp. 221-226, 12-14 October 2009.
- [25] M. Yavuz, F. Meshkati, S. Nanda, A. Pokhariyal, N. Johnson, B. Raghothaman, and A. Richardson, "Interference management and performance analysis of UMTS/HSPA+ femtocells," *IEEE Communications Magazine*, vol. 47, no. 9, pp. 102-109, September 2009.
- [26] D.-C. Oh, H.-C. Lee, and Y.-H. Lee, "Cognitive radio based femtocell resource allocation," *International Conference on Information and*

Communication Technology Convergence (ICTC), pp. 274-279, 17-19 November 2010.

- [27] P. Lee, T. Lee, J. Jeong, and J. Shin, "Interference management in LTE femtocell systems using fractional frequency reuse," *The 12th International Conference on Advanced Communication Technology (ICACT)*, vol. 2, pp. 1047-1051, 7-10 February 2010.
- [28] Z. Bharucha, H. Haas, G. Auer, and I. Cosovic, "Femto-Cell resource partitioning," *IEEE GLOBECOM Workshops*, pp. 1-6, 30 November-4 December 2009.
- [29] Y. Wang, K. Zheng, X. Shen, and W. Wang, "A distributed resource allocation scheme in femtocell networks," *IEEE 73rd Vehicular Technology Conference (VTC Spring)*, pp. 1-5, 15-18 May 2011.
- [30] M. S. Jin, S. A. Chae, and D. I. Kim, "Per cluster based opportunistic power control for heterogeneous networks," *IEEE 73rd Vehicular Technology Conference (VTC Spring)*, pp. 1-5, 15-18 May 2011.
- [31] V. Chandrasekhar, M. Kountouris, and J. G. Andrews, "Coverage in multi-antenna two-tier networks," *IEEE Transactions on Wireless Communications*, vol. 8, no. 10, pp. 5314-5327, October 2009.
- [32] S. Guruacharya, D. Niyato, E. Hossain, D. I. Kim, "Hierarchical competition in femtocell-based cellular networks," *IEEE Global Telecommunications Conference (GLOBECOM)*, pp. 1-5, 6-10 December 2010.
- [33] H. Li, X. Xu, D. Hu, X. Qu, X. Tao, and P. Zhang, "Graph method based clustering strategy for femtocell interference management and spectrum efficiency improvement," *6th International Conference on Wireless Communications Networking and Mobile Computing (WiCOM)*, pp. 1-5, 23-25

September 2010.

- [34] H. Widiarti, S.-Y. Pyun, and D.-H. Cho, "Interference mitigation based on femtocells grouping in low duty operation," *IEEE 72nd Vehicular Technology Conference Fall (VTC Fall)*, pp. 1-5, 6-9 September 2010.
- [35] I. Guvenc, M.-R. Jeong, M. E. Sahin, H. Xu, and F. Watanabe, "Interference avoidance in 3GPP femtocell networks using resource partitioning and sensing," *IEEE 21st International Symposium on Personal, Indoor and Mobile Radio Communications Workshops (PIMRC Workshops)*, pp. 163-168, 26-30 September 2010.
- [36] L. Zhang, L. Yang, and T. Yang, "Cognitive interference management for LTE-A femtocells with distributed carrier selection," *IEEE 72nd Vehicular Technology Conference Fall (VTC Fall)*, pp. 1-5, 6-9 September 2010.
- [37] M. E. Sahin, I. Guvenc, M.-R. Jeong, and H. Arslan, "Handling CCI and ICI in OFDMA femtocell networks through frequency scheduling," *IEEE Transactions on Consumer Electronics*, vol. 55, no. 4, pp. 1936-1944, November 2009.
- [38] Femtoforum website, <http://www.smallcellforum.org/about-us-what-we-do-objectives-and-scope>, retrieved on 11 January 2013.
- [39] 3GPP website, <http://www.3gpp.org/World-s-first-femtocell-standard>, retrieved on 10 March 2013.
- [40] 3GPP TR36.921, "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); FDD Home eNode B (HeNB) Radio Frequency (RF) requirements analysis (Release 9)," April 2010.
- [41] 3GPP TR36.921, "3GPP; Technical Specification Group Radio Access Network Evolved Universal Terrestrial Radio Access (E-UTRA); FDD

Home eNode B (HeNB) Radio Frequency (RF) requirements analysis (Release 11)," October 2012.

- [42] Vodafone UK website, <http://shop.vodafone.co.uk/shop/mobile-accessories/sure-signal>, retrieved on 12 March 2013.
- [43] Verizon Wireless website, http://support.verizonwireless.com/information/network_extender.html, retrieved on 12 March 2013.
- [44] Wikipedia, [http://en.wikipedia.org/wiki/White_spaces_\(radio\)](http://en.wikipedia.org/wiki/White_spaces_(radio)), retrieved on 16 August 2011.
- [45] M. Nekovee, "Quantifying the availability of TV White Spaces for cognitive radio operation in the UK," *IEEE International Conference on Communications Workshops*, pp. 1-5, 14-18 June 2009.
- [46] Ofcom, "Award of the 800 MHz and 2.6 GHz spectrum bands – Publication of final results of auction under regulation 111 of the Wireless Telegraphy (Licence Award) Regulations 2012", 1 March 2013.
- [47] Ofcom, "Securing long term benefits from scarce low frequency spectrum - UHF strategy statement", 16 November 2012.
- [48] M. Nekovee, "A survey of cognitive radio access to TV White Spaces," *International Conference on Ultra Modern Telecommunications & Workshops (ICUMT)*, pp. 1-8, 12-14 October 2009.
- [49] C. Cordeiro, K. Challapali, and D. Birru, "IEEE 802.22: An introduction to the first worldwide wireless standard based on cognitive radios," *Journal of Communications*, vol. 1, no. 1, pp. 38-47, December 2006.
- [50] F. L. Martin, N. S. Correal, R. L. Ekl, P. Gorday, and R. O'Dea, "Early opportunities for commercialization of TV Whitespace in the U.S," *3rd International Conference on Cognitive Radio Oriented Wireless Networks and*

Communications (CrownCom), pp. 1-5, 15-17 May 2008.

- [51] Federal Communications Commission, Spectrum Policy Task Force, "Report of the Spectrum Efficiency Working Group," available at <http://www.fcc.gov/sptf/reports.html>, 15 November 2004.
- [52] Federal Communications Commission (FCC) 08-260, "Second Report and Order and Memorandum Opinion and Order in ET Docket Nos. 02-380 (Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band) and 04-186 (Unlicensed Operation in the TV Broadcast Bands)," 14 November 2008.
- [53] Ofcom, Digital Dividend Review, "A statement on our approach to awarding the digital dividend," 13 December 2007.
- [54] European Commission, Radio Spectrum Policy Group, "RSPG opinion on cognitive technologies", February 2011.
- [55] ECC Report 159, "Technical and Operational Requirements For The Possible Operation of CR Systems In The White Space (470-790MHz)," January 2011.
- [56] ECC report 185, "Complementary Report to ECC Report 159 further definition of technical and operational requirements for the operation of white space devices in the band 470-790 MHz," January 2013.
- [57] ECC report 186, "Technical and operational requirements for the operation of white space devices under geo-location approach," January 2013.
- [58] Ofcom, Digital dividend, "Cognitive Access--Consultation on license-exempting cognitive devices using interleaved spectrum," February 2009.
- [59] Ofcom, "Draft Annual Plan 2012/13," 17 February 2012.

- [60] Ofcom, "Implementing Geolocation Summary of consultation responses and next steps," 1 September 2011.
- [61] Ofcom, "TV white spaces a consultation on whitespace device requirements," 10 January 2013.
- [62] CogNeA website, <http://www.cognea.org/index.html>, retrieved on 2 March 2013.
- [63] Ecma-392 website, <http://www.ecma-international.org/publications/standards/Ecma-392.htm>, retrieved on 15 March 2013.
- [64] J. Wang, M.-S. Song, S. Santhiveeran, K. Lim, G. Ko, K. Kim, S.-H. Hwang, M. Ghosh, V. Gaddam, and K. Challapali, "First cognitive radio networking standard for personal/portable devices in TV White Spaces," *IEEE Symposium on New Frontiers in Dynamic Spectrum*, pp. 1-12, 6-9 April 2010.
- [65] IEEE 802.11af Task Group, http://www.ieee802.org/11/Reports/tgaf_update.htm, retrieved on 15 March 2013.
- [66] IEEE project P1900.7 website, <http://standards.ieee.org/develop/project/1900.7.html>, retrieved on 15 July 2013.
- [67] QoSMOS Deliverable 8.9, "Standardization and Dissemination version 3," available at <http://www.ict-qosmos.eu/dissemination/deliverables.html>, 31 December 2012.
- [68] IETF PAWS working group website, <https://datatracker.ietf.org/wg/paws/charter/>, retrieved on 15 July 2013.
- [69] Weightless website, <http://www.weightless.org/>, retrieved on 12 March

2013.

- [70] NICT website, <http://www.nict.go.jp/en/press/2012/10/17-1.html>, retrieved on 17 October 2012.
- [71] NICT website, <http://www.nict.go.jp/en/press/2013/01/30-1.html>, retrieved on 30 January 2013.
- [72] Centre for White Space Communications, <http://www.wirelesswhitespace.org/news/white-space-news/neul-releases-first-tv-white-space-asic.aspx>, retrieved on 12 February 2013.
- [73] Ofcom, "Digital dividend - Geolocation for Cognitive Access-A discussion on using geolocation to enable license-exempt access to the interleaved spectrum," 17th November 2009.
- [74] Brithsh Telecom Report, "Response to Ofcom Consultation on Digital Dividend: Cognitive Access," April 2009.
- [75] Ofcom, "Consultation - Implementing Geolocation," 9 November 2010.
- [76] COGEU project website, <http://www.ict-cogeu.eu/index.htm>, retrieved on 11 March 2013.
- [77] QoSMOS project website, <http://www.ict-qosmos.eu/home.html>, retrieved on 11 March 2013.
- [78] Centre for White Space Communications, <http://www.wirelesswhitespace.org/news/white-space-news/fcc-to-commence-trial-of-google-white-space-database.aspx>, retrieved on 28 February 2013.
- [79] Centre for White Space Communications, <http://www.wirelesswhitespace.org/news/white-space-news/tv-white-space-opens-nationwide-in-the-us.aspx>, retrieved on 1 March 2013.

- [80] Google blog, <http://blog.google.org/2013/03/tv-white-spaces-trial-launches-in-south.html>, retrieved on 25 March 2013.
- [81] R. MacKenzie, O. Grøndalen, and P. H. Lehne, "Economic evaluation of rural broadband and machine-to-machine deployments in TV Whitespaces," *European Wireless*, April 2013.
- [82] M. Nekovee, "A survey of cognitive radio access to TV White Spaces," *International Journal of Digital Multimedia Broadcasting*, vol. 2010, article ID. 236568, 11 pages, 2010.
- [83] R. Ahuja, R. Corke, and A. Bok, "Cognitive radio system using IEEE 802.11a over UHF TVWS," *3rd IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks*, pp. 1-9, 14-17 October 2008.
- [84] D. P. Bertsekas, *Nonlinear Programming (Second edition)*, Athena Scientific, 1999.
- [85] P. T. Boggs and J. W. Tolle, "Sequential Quadratic Programming," *Acta Numerica*, vol. 4, pp. 1-51, January 1995.
- [86] R. B. Wilson, "A simplicial algorithm for concave programming," Ph.D. dissertation, Graduate School of Business Administration, Harvard University, Cambridge, MA, 1963.
- [87] S.-P. Han, "A globally convergent method for nonlinear programming," *Journal of Optimization Theory and Applications*, vol. 22, no. 3, pp. 297-309, 1977.
- [88] M. J. D. Powell, "A fast algorithm for nonlinearly constraint optimization calculations," *Numerical Analysis, Lecture Notes in Mathematics*, vol. 630, pp. 144-157, 1978.
- [89] K. Schittkowski and Y.-X. Yuan, *Sequential quadratic programming methods*,

Wiley Encyclopedia of Operations Research and Management Science, 2011.

- [90] "Guidelines for evaluation of radio transmission technologies for IMT-2000," *International Telecommunication Union (ITU) Recommendation M.1225*, 1997.
- [91] 3GPP, "Simulation assumptions and parameters for FDD HeNB RF requirements," 3GPP TSG RAN WG4 R4-092042, May 2009.
- [92] 3GPP, "HNB and HNB-Macro Propagation Models," 3GPP TSG RAN WG4 R4-071617, October 2007.
- [93] X. Lin and Y. Fang, "A survey on the available digital TV bands for cognitive radio operations," *4th International Conference on Communications and Networking in China (ChinaCOM)*, pp. 1-7, 26-28 August 2009.
- [94] Ofcom, "Digital Switchover Transmitter Details", available at <http://stakeholders.ofcom.org.uk/broadcasting/guidance/tech-guidance/dsodetails/>.
- [95] IEEE 802.22 Working Group of the LAN/MAN Standards Committee, "IEEE P802.22/ DRAFTv1.0 Draft Standard for Wireless Regional Area Networks Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Policies and procedures for operation in the TV Bands," 2006.
- [96] D. Gurney, G. Buchwald, L. Ecklund, S. Kuffner, and J. Grosspietsch, "Geo-Location database techniques for incumbent protection in the TV White Space," *3rd IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks*, pp. 1-9, 14-17 October 2008.
- [97] FCC, "In the Matter of Unlicensed Operation in the TV Broadcast Bands,

additional spectrum for unlicensed devices below 900MHz and in the 3GHz band”, ET Docket No. 04-186, Notice of Proposed Rulemaking, FCC OET, May 2004.

- [98] Digital UK, <http://www.digitaluk.co.uk/>, retrieved on 2 April 2013.
- [99] Digital UK, “DTV transmitter information in Newcastle”, <http://www.digitaluk.co.uk/coveragechecker/main/trade/NE1+2ST/NA/0/NA>, retrieved on 2 April 2013.
- [100] Ofcom, “Digital Dividend: Geolocation for Cognitive Access-A discussion on using geolocation to enable license-exempt access to the interleaved spectrum,” 17 November 2009.
- [101] P. Xia, V. Chandrasekhar, and J. G. Andrews, "Open vs. closed access femtocells in the uplink," *IEEE Transactions on Wireless Communications*, vol. 9, no. 12, pp. 3798-3809, December 2010.
- [102] P. Zhang, Y. Chen, Z. Feng, Q. Zhang, Y. Li, and L. Tan, "Joint power control and scheduling strategies for OFDMA femtocells in hierarchical networks," *IEEE 73rd Vehicular Technology Conference (VTC Spring)*, pp. 1-5, 15-18 May 2011.
- [103] Z. Bharucha, A. Saul, G. Auer, and H. Hass, “Dynamic resource partitioning for downlink femto-to-macro-cell interference avoidance,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2010, article ID. 143413, pp. 1-13, January 2010.
- [104] L. T. W. Ho, and H. Claussen, "Effects of user-deployed, co-channel femtocells on the call drop probability in a residential scenario," *IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pp. 1-5, 3-7 September 2007.
- [105] J. Ling, D. Chizhik, and R. Valenzuela, "On resource allocation in dense

- femto-deployments," *IEEE International Conference on Microwaves, Communications, Antennas and Electronics Systems (COMCAS)*, pp. 1-6, 9-11 November 2009.
- [106] C. E. Shannon, "A mathematical theory of communication," *The Bell System Technical Journal*, vol. 27, pp. 379-423, July 1948.
- [107] W. Sun, and C. Xu, *Optimization Method*, Higher Education Press, 2010.